# Accelerator Driven Inertial Confinement Fusion

Peter Seidl (LBNL)

PASeidl@lbl.gov

for the for the Heavy-Ion Fusion Science Virtual National Laboratory (HIFS-VNL)

http://www-afrd.lbl.gov/fusion.html

LBNL, LLNL, PPPL

We have also collaborated with: NRL, LANL, SNL, Univ. of Maryland, Univ. of Missouri Rolla, Stanford Linear Accelerator Center, MIT Advanced Magnet Laboratory, Univ. of California (Berkeley, Los Angeles, and San Diego) Georgia Tech, GSI, Mission Research Corporation, General Atomics Advanced Ceramics, Idaho National Environmental and Engineering Laboratory, Allied Signal, National Arnold, Hitachi, MRTI

Presented to NE C282, Nuclear Engineering Department, UC Berkeley
November 4, 2009

# The advantages of heavy ion fusion (HIF), identified in many past reviews [1], still apply now:

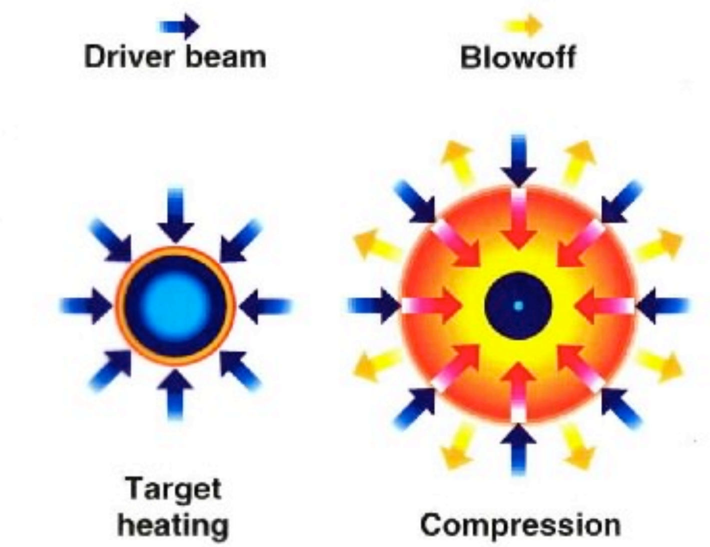
1. **Accelerators** with **total beam energy** of ≥ 1 MJ have separately exhibited **intrinsic efficiencies**, **pulse repetition rates** (>100 Hz), **power levels** (TW), and **durability** required for IFE.
2. **Thick-liquid protected target chambers are designed to have 30-year plant lifetimes.** These designs are compatible with indirect-drive target illumination geometries, which will be tested in NIF experiments. **Thick-liquid protection** [2] with molten salt having high thermal and radiation stability (LiF-$BeF_2$, or flibe) has been a **standard aspect of most HIF power plant concepts**.
3. Focusing magnets for ion beams **avoid most of the direct line-of-sight damage from target debris, neutron and $\gamma$ radiation**. Thus, only the final focusing magnet coils need to be hardened or shielded from the neutrons.
4. Power plant studies have shown attractive economics and environmental characteristics (only **class-C low level waste**) [3]. Accelerator design efforts have converged on **multiple heavy ion beams** accelerated by **induction acceleration**. After acceleration to the final ion kinetic energy, the beams, which are non-relativistic, are compressed axially to the 4-30 ns duration, (few-hundred TW peak power) required by the target design. Simultaneously they are focused to a few millimeter spot on the fusion target.

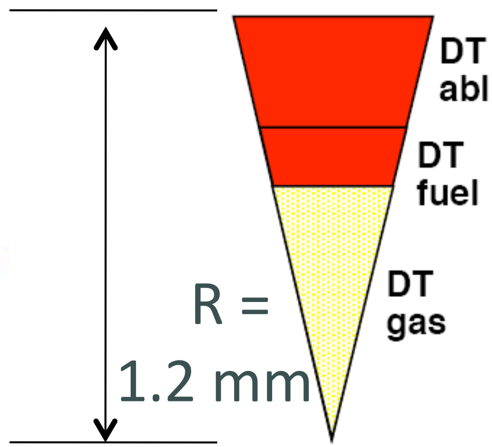
# Outline

1. Overview of concept
2. Inertial fusion target design
3. Reactor chamber
4. Beam physics issues and accelerator design
5. Next steps

## Direct drive targets

Beams deposited in the fusion target, rocket effect drives implosion and ignition. Capable of the highest gain. Illumination geometry must be very precise.




**Example direct drive target**

Beam spot 0.3 mm – 1.2 mm

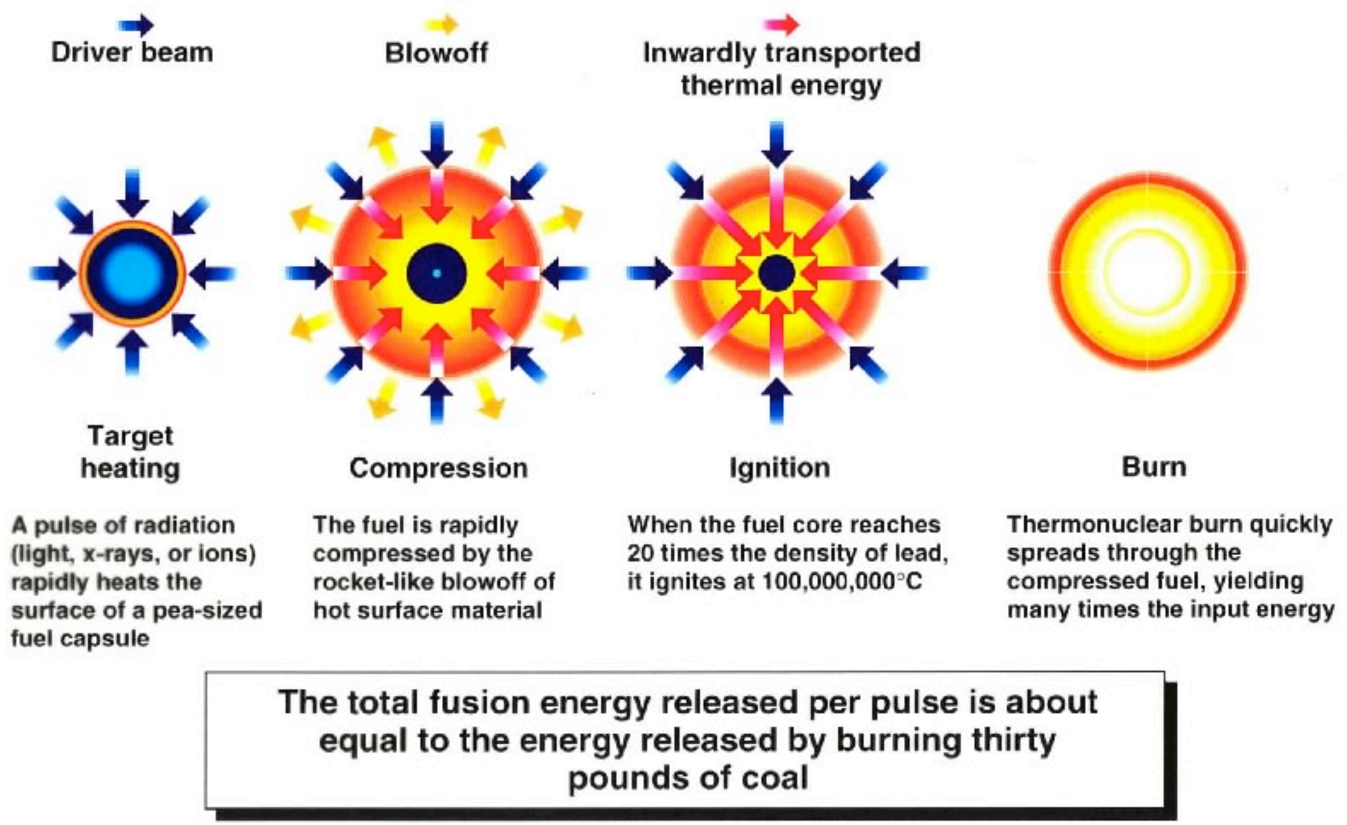
0.5 MJ beam energy

Gain = 47

$E_{beam}$ = 0.050 – 0.5 GeV, $Rb^+$

B.G. Logan, et al., Phys. Plasmas (2008)

# Inertial confinement fusion concept

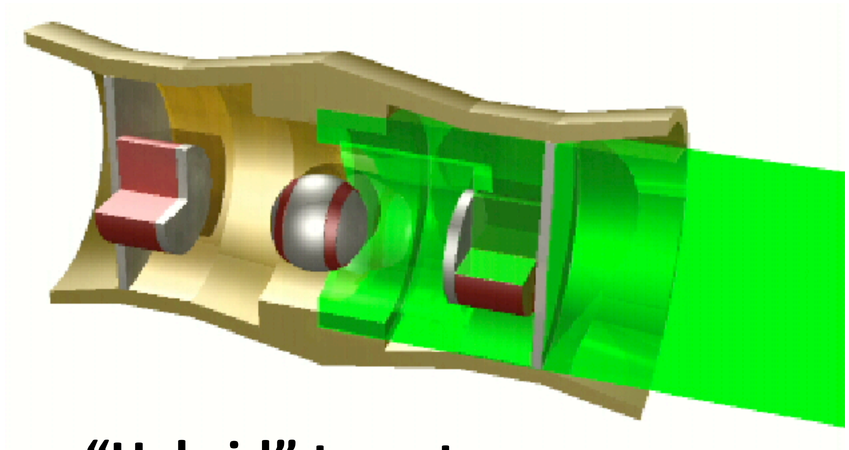



Rayleigh – Taylor Instability, In-flight aspect ratio: $25 < R/\Delta R < 35$,
~ 100 Mbar, $10^{14}$ - $10^{15}$ W, $v_{imp} \approx 3\text{-}4 \times 10^7$ cm/s

*See, e.g.:, Lindl, Inertial Confinement Fusion, AIP Press, 1998*

# Most HIF systems studies have used indirect drive targets

Beams strike both ends of a “hohlraum”, producing a unform bath of X-rays which heat and compress the fusion capsule.



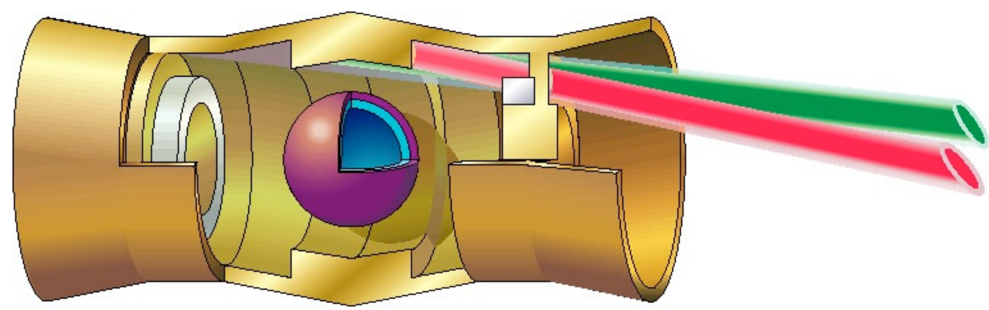
**<u>“Hybrid” target</u>**

Beam spot 3.8 mm x 5.4 mm

6.7 MJ beam energy

Gain = 58

$E_{beam}$ = 3 – 4.5  GeV, $Pb^{+}$



**<u>“Distributed Radiator” target</u>**

Beam spot 1.8 mm x 4.1 mm

5.9 MJ beam energy

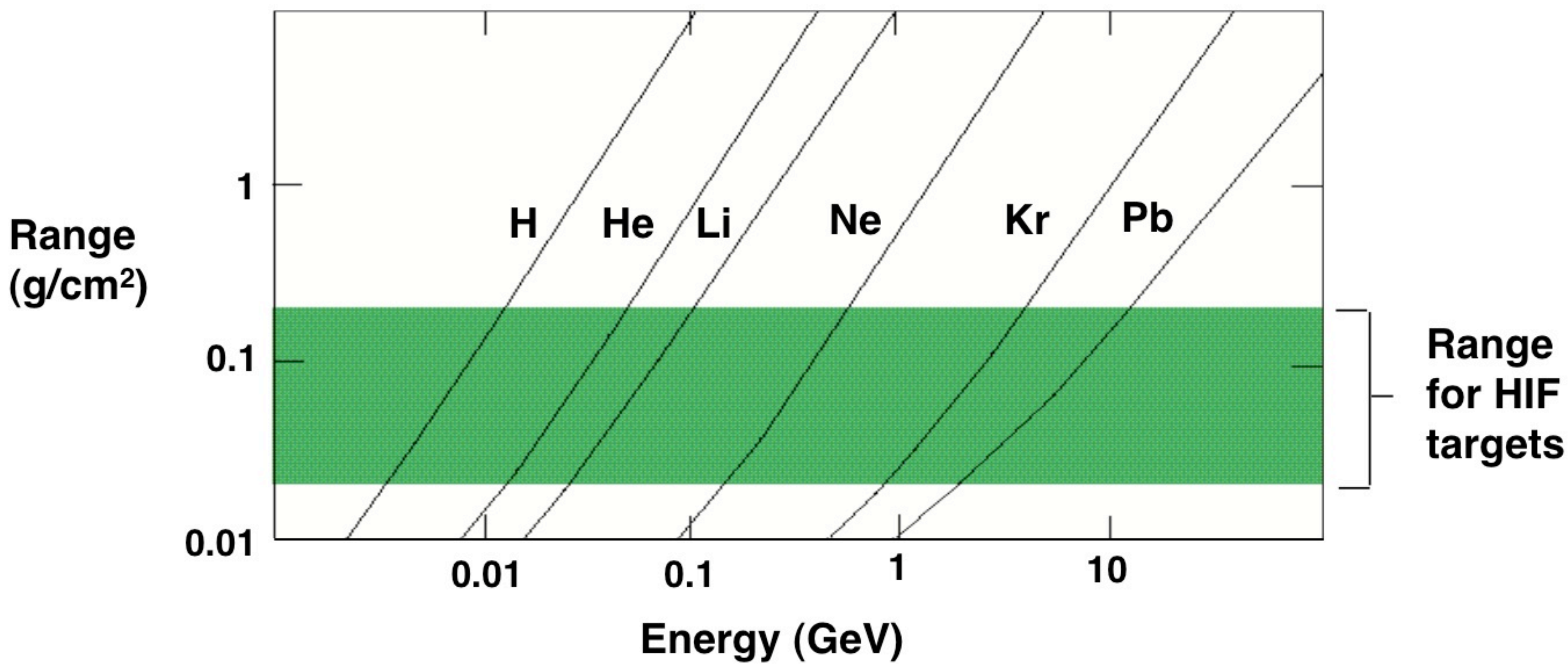
Gain = 68,

$E_{beam}$ = 3.3 - 4  GeV, $Pb^{+}$

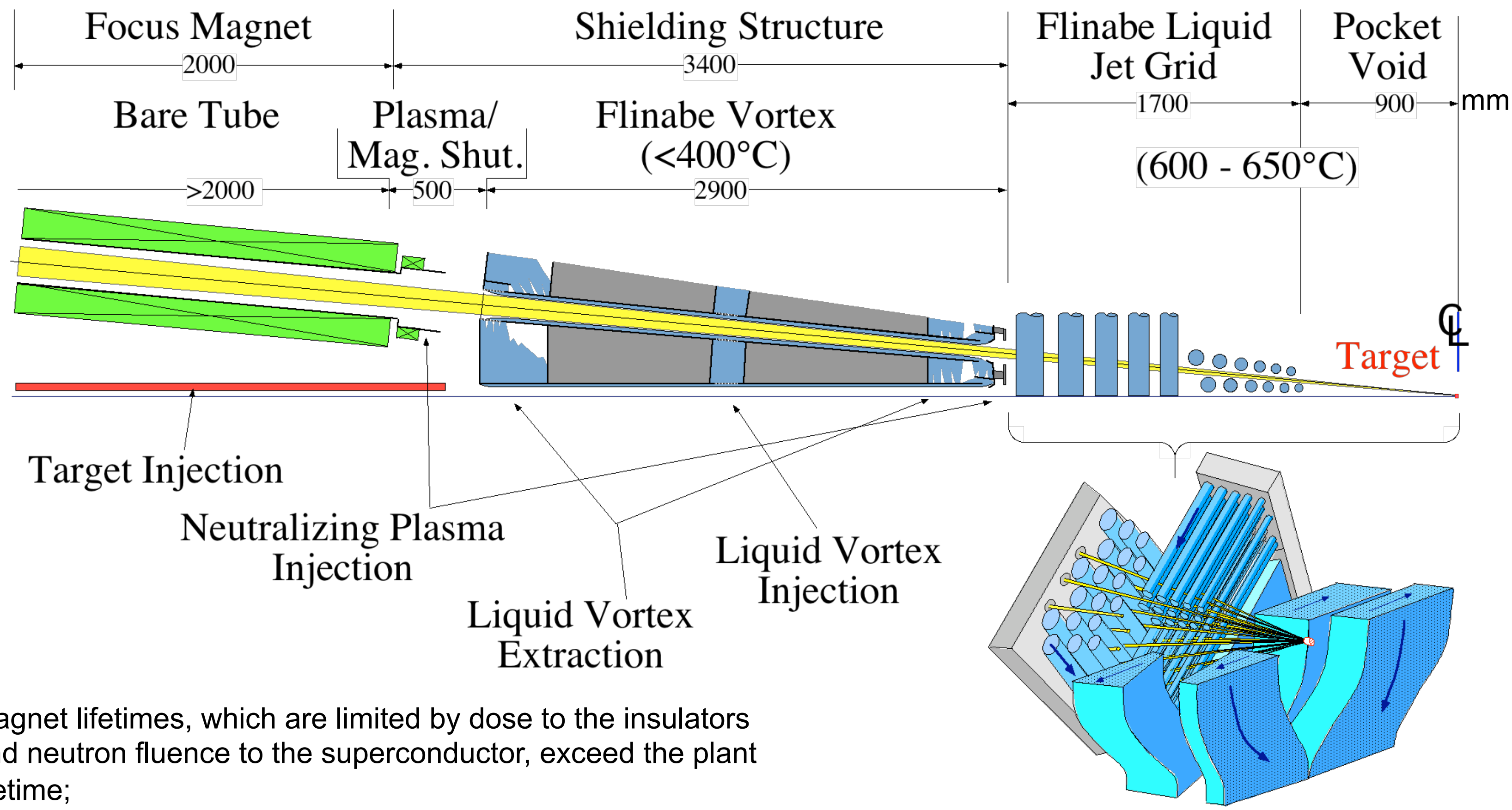
D. Callahan et al., Laser and Particle Beams (2002)

**<u>Indirect drive concept will soon be tested at the National Ignition Facility (LLNL)</u>**

# Heavier Ions ⇒ Higher Kinetic Energy & lower beam current



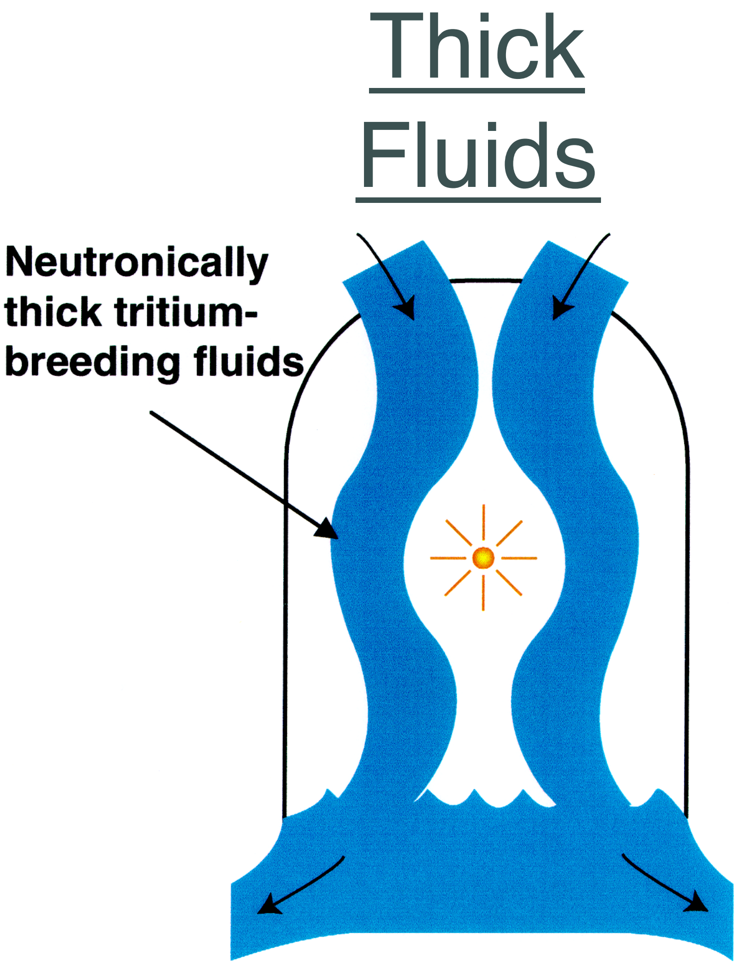
# The first wall problem? Design beam line for HIF illustrates liquid wall protection

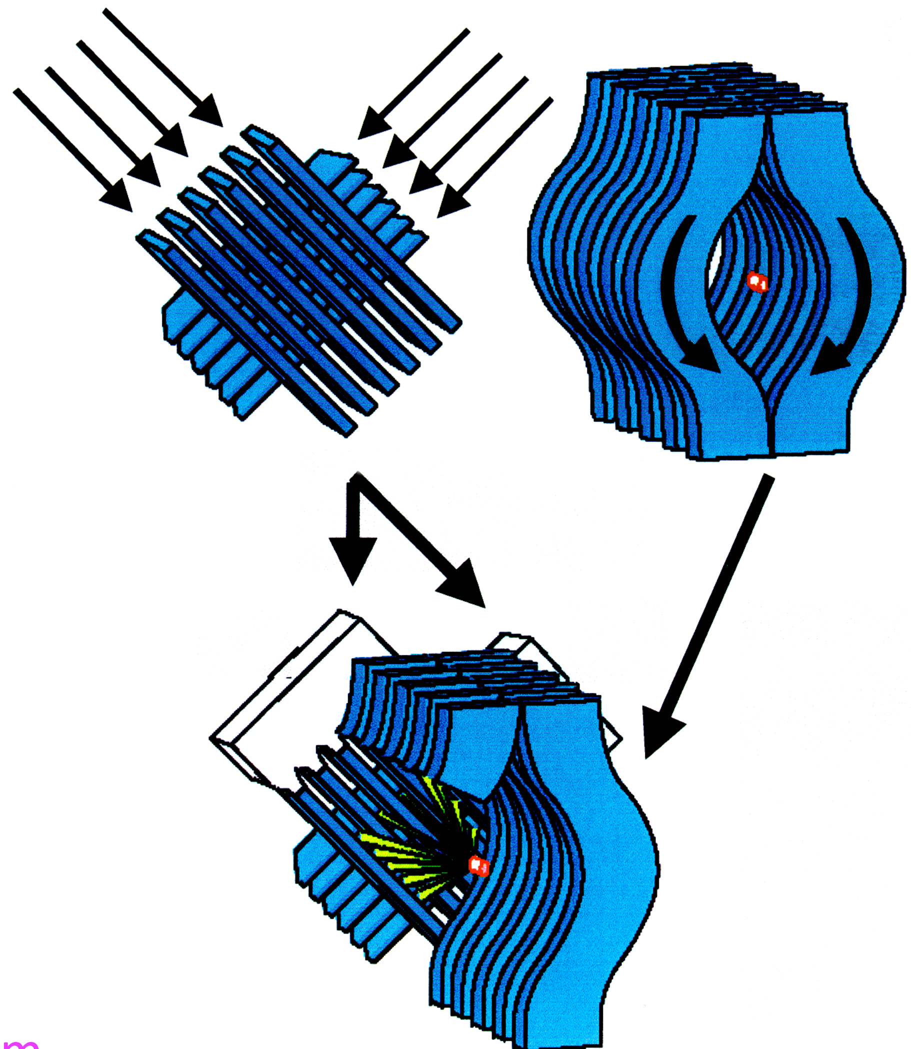



Schematic Liquid Jet Geometry

Magnet lifetimes, which are limited by dose to the insulators and neutron fluence to the superconductor, exceed the plant lifetime;
Insulator & superconductor lifetimes (in years) are:
Last magnet: 230/260
2nd magnet: 410/1580
3rd magnet: 100/610

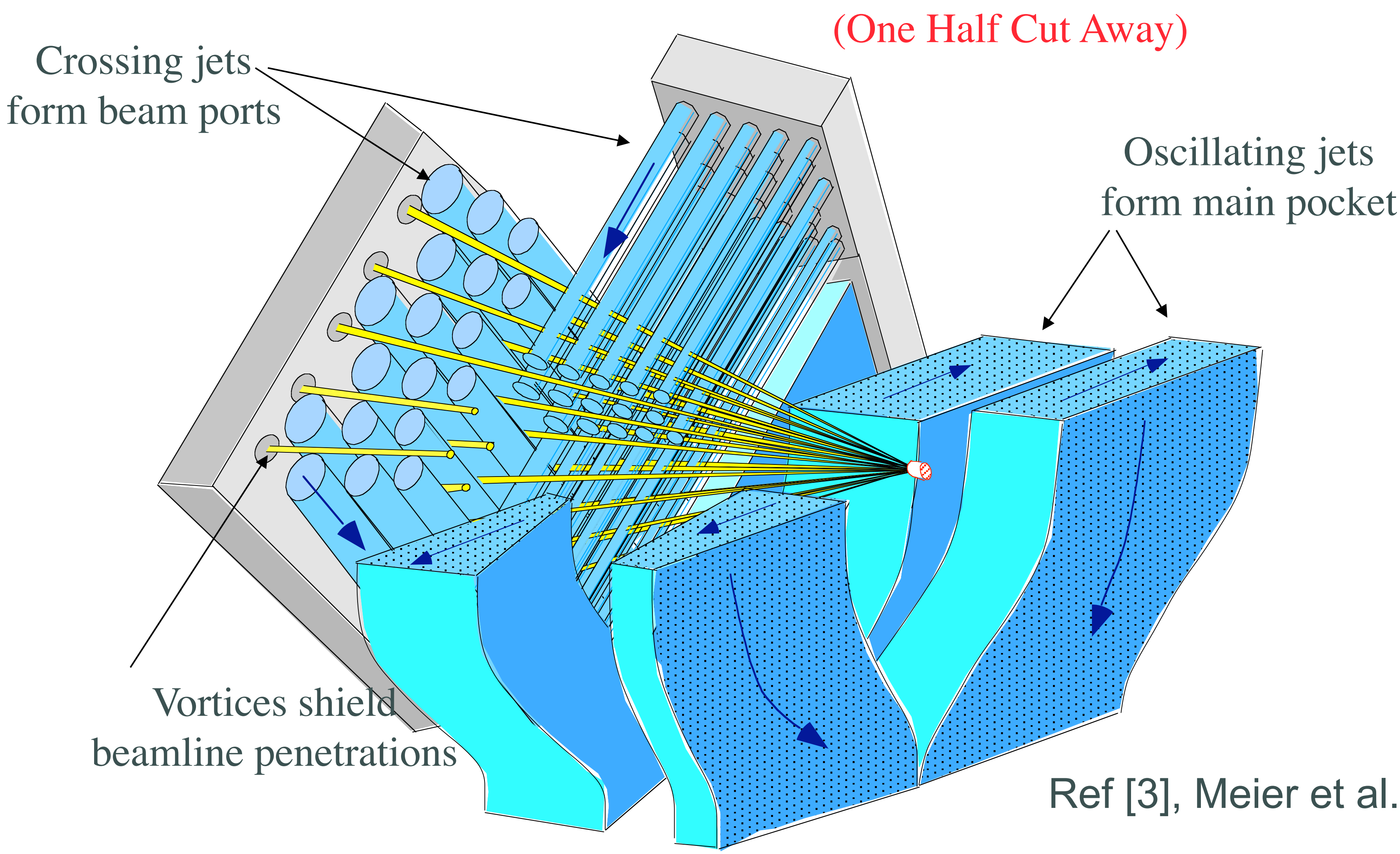
# Multiple jets can create thick liquid pockets



FLiBe – fluorine, lithium, beryllium

# The First Wall is Protected by Neutron-thick Molten Salt (FLiBe)




Ref [3], Meier et al.

# Hybrid fusion – fission

**Combine an ion beam driven fusion neutron source with a fission blanket.**

**Potential benefit of transmuting the long-lived radioactive byproducts of fission-based nuclear reactors, thus dramatically reducing the nuclear waste problem.**

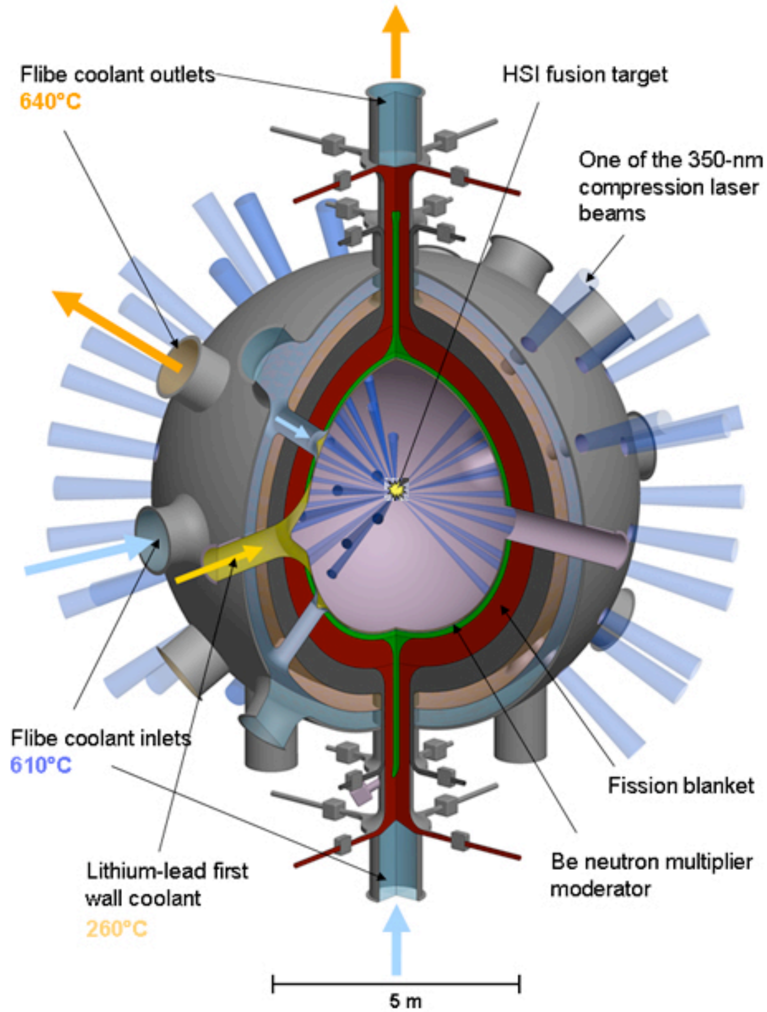
**Fission gain relaxes required fusion gain.**

Hybrids in the news:
Nature, Phys. Today, NYTimes:
http://web.mit.edu/fusion-fission

Attempt to **preserve** the significant advantage of **thick liquid protection** of the reactor chamber structural wall.

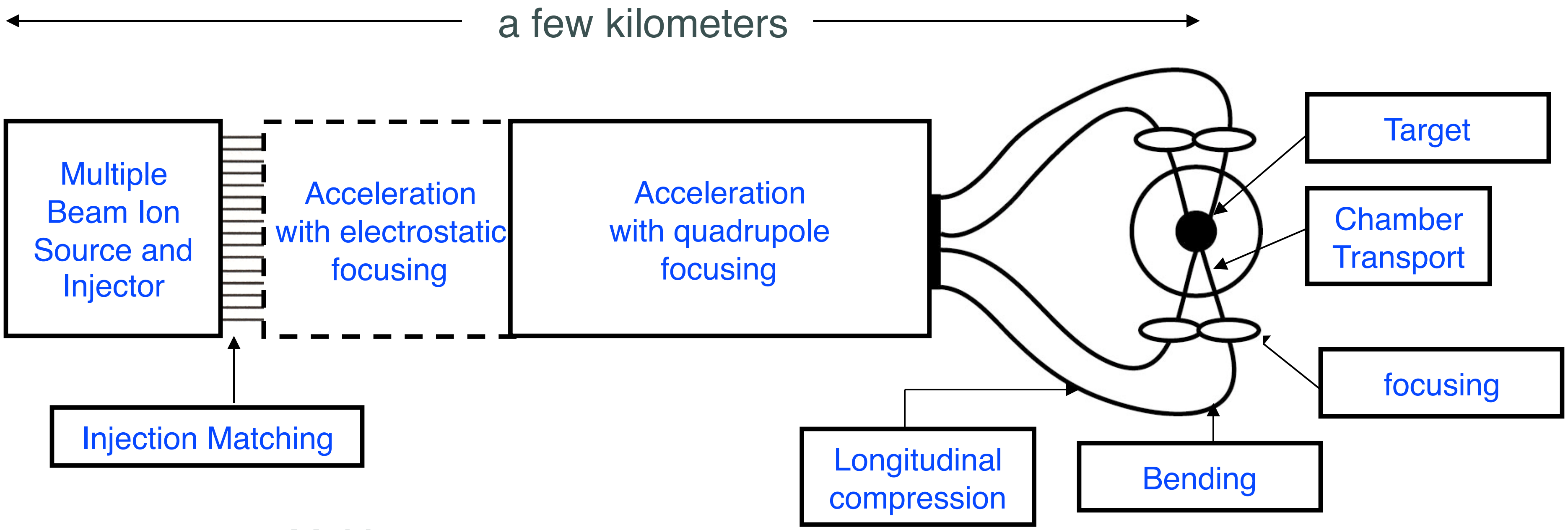
- **Can flowing liquid jets feasibly contain the fissile material? Dissolving in molten salt: material handling challenges. Fuel contained in TRISO pebbles. Hydraulic challenges**
- **Or thin liquid jets, allowing a moderated flux of neutrons to reach a fissile blanket behind a solid structural wall?**

# NIF ignition, LLNL LIFE proposal, may motivate renewed interest in IFE




LLNL: https://lasers.llnl.gov/about/missions/energy_for_the_future/life/

# Accelerator for heavy ion inertial fusion: An Induction Linac "Driver"




| | | |
|---|---|---|
| ~2-3 MeV | ~3 GeV | ~3 GeV |
| ~1 A/beam | ~200 A/beam | ~4000 A/beam |
| ~20 μs | ~200 ns | ~10 ns |
| $L_b$ = 27 m (A=208) | 10 m | 0.5 m |

Power amplification to the required $10^{14}$ to $10^{15}$ W is achieved by acceleration and longitudinal bunching.

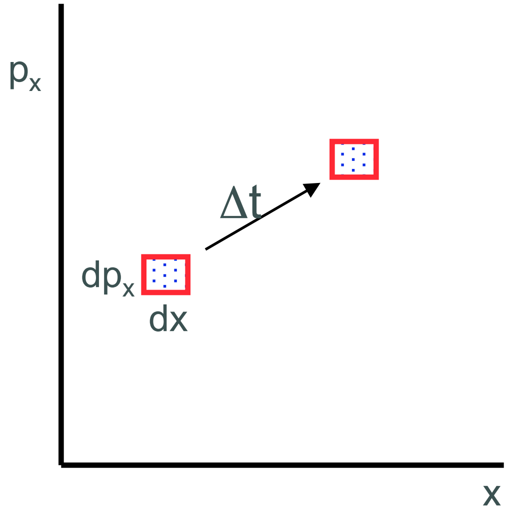
# Physics Context of the Heavy Ion Beams

A conserved quantity

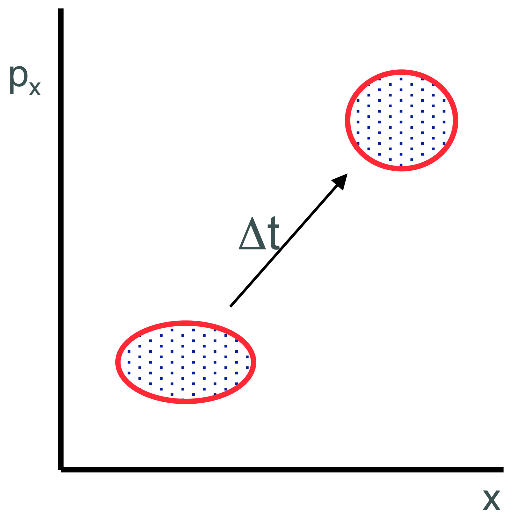
&

Forces in the problem

# A very general conservation law governs the motion of the particles in the accelerator




Infinitesimal volume in phase space keeps its density through time, unless non-conservative forces act on it (e.g., it hits something).



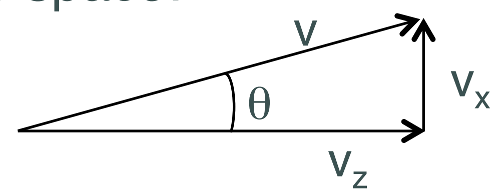

An extended shape might change it's shape, but to keep local density everywhere the same, if it stretched in one direction, it shrinks by the same amount in another $\Longrightarrow$

$\boxed{\text{Phase space volume of the beam is constant.}}$

Liouville Theorem

# The "emittance" is proportional to the beam phase space area, and therefore conserved

Area of (upright) uniform density ellipse in phase space:




$$= \pi\, x_{max} p_{x\,max}$$

$$= \pi\, x_{max} m\gamma \frac{v_{x\,max}}{v_z} v_z$$

$$\propto\ \beta\gamma\, x_{max}\theta_{max}$$

where $\beta = v_z/c$.

Define *EMITTANCE* :

$$\varepsilon_x = x_{max}\theta_{max}$$

x Emittance

$$\boxed{\varepsilon_{nx} = \beta\gamma\, x_{max}\theta_{max}}$$

Normalized x emittance

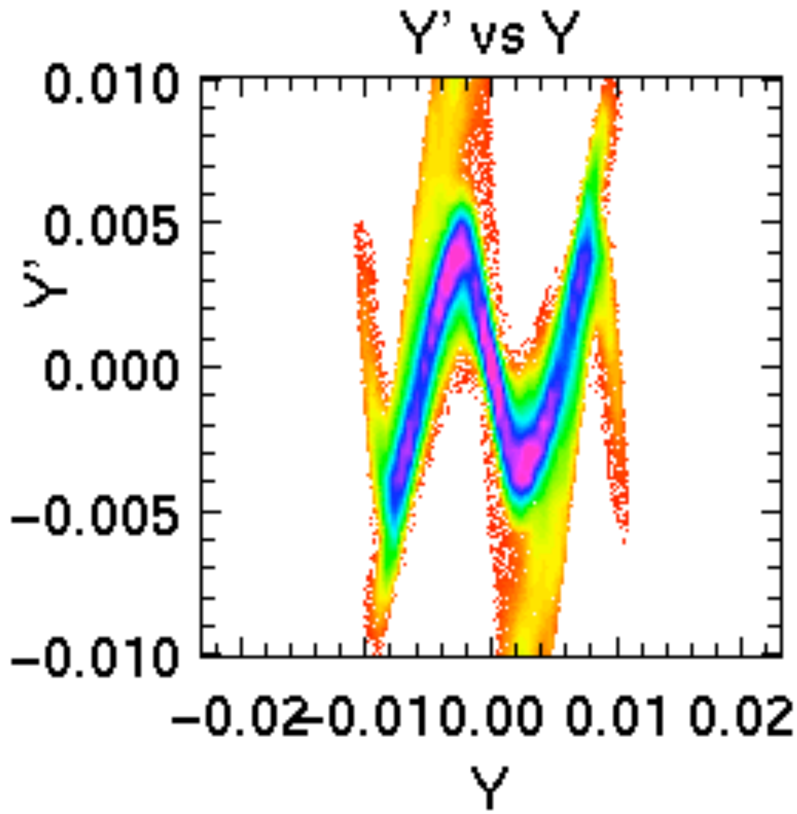
Normalized emittance is conserved for conservative forces

Small emittance = Cold beam

# What do we need to keep the beam contained in a small phase space volume?

Normalized emittance is conserved.

But phase space can get wild …



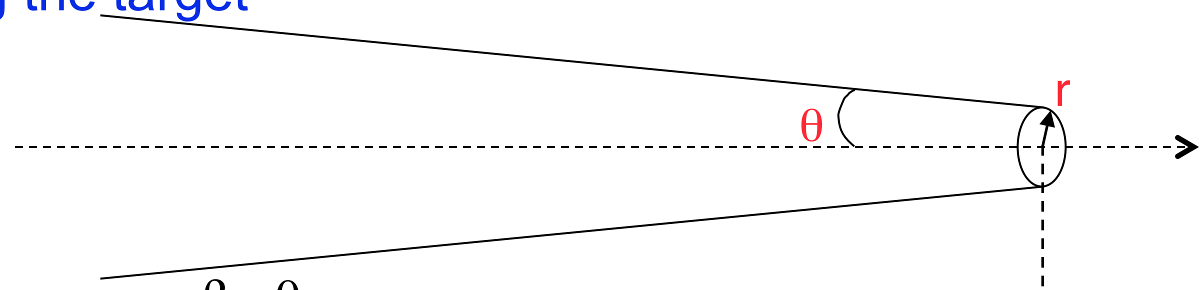

Effectively, beam is bigger in phase space ⇒ doesn't focus to a small spot

Linear forces don't do this-- they keep phase space elliptical. So ...
Keep the forces linear!

Luckily-- Space charge forces of a uniform density elliptical beam are linear!

# Emittance determines how small can we make the beam focal spot

Beam approaching the target




$\varepsilon \approx \beta\gamma r\theta$

$$\boxed{r \approx \frac{\varepsilon}{\beta\gamma\theta}}$$

(space charge neglected)

$\theta$ is limited by geometric aberrations of final focus lenses, so

r is determined by the transverse emittance.

## The accelerator designer's job is to keep the effective emittance low.

A heavy ion driver requires final transverse emittance ≤ 10 $\pi$ mm-mrad (approximately).

# The beam must be cold longitudinally also ...

Effect of chromatic aberrations (different particles have different energies):

A focusing magnet is less effective on higher energy particles

$$\theta \propto \frac{1}{p_z} \quad \Rightarrow \quad \frac{\delta\theta}{\theta} = -\frac{\delta p_z}{p_z}$$

(single lens)

$$\delta r = s\,\delta\theta = s\,\theta\,\frac{\delta p_z}{p_z}$$

(coefficient ~6 for a realistic lens system)

So keep the beam as close as possible to single energy (cold, low $\varepsilon_z$), and design the magnet for that energy. Requirements are $dp_z/p_z \leq 0.5\%$, unless an achromatic focusing system capable of much greater spread can be invented.

The accelerator designer's job is to keep the effective <u>longitudinal and transverse</u> emittance low.

# Forces that Oppose the Focus

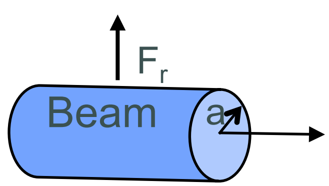
# The forces of space charge and "thermal" compete with any force focusing the beam

## Space Charge Force

$$\vec{F} = q\vec{E}$$

$$\int \vec{E} \bullet \vec{n}\, da = \frac{Q}{\varepsilon_0} \quad \Rightarrow \quad E_r = \frac{\lambda}{2\pi} \frac{r}{a^2}$$

$$E(a) = \frac{\lambda}{2\pi} \frac{1}{a}$$




$$\boxed{F_r \propto \frac{1}{a}}$$

## Thermal Force (determined by emittance)

$$P(a) = \frac{NkT}{V} \propto \frac{T}{V} \propto \frac{v_{rms}^2}{a^2}$$

$$a^2 v_{rms}^2 \propto \text{emittance} = \text{constant} \quad \Rightarrow$$

$$P(a) \propto \frac{1}{a^4}$$

$$F_r(a) = P_r(a)A = P_r(a) 2\pi a l$$

$$\boxed{F_r \propto \frac{1}{a^3}}$$

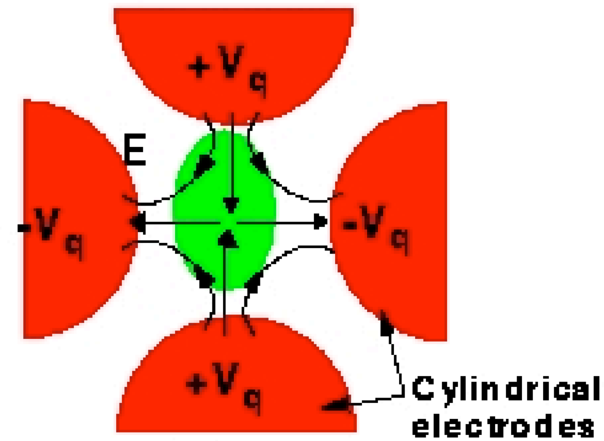
Doesn't depend on charge

**Space charge dominates in the accelerator. Thermal force dominates at final focus to a spot, where "a" is very small.**

# The Accelerator-- Acceleration + Focusing

# Beam Focusing in High Energy Accelerators is Usually Done with Quadrupoles

Quadrupoles focus in one dimension and defocus in the other.




Electric quad

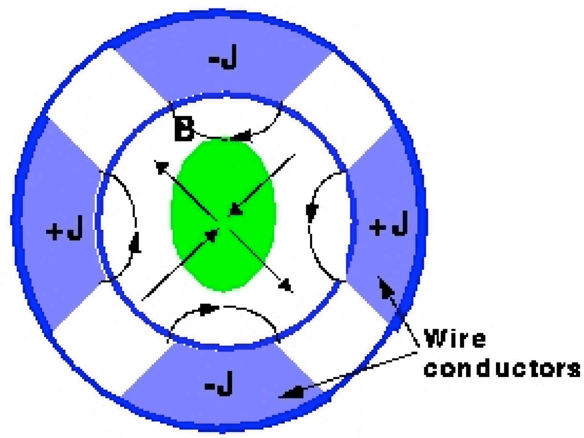
The forces on the beam are linear:

$F_x = + qE' \, x$ or $+ qvB' \, x$

$F_y = - qE' \, y$ or $- qvB' \, y$

$$E' \equiv \frac{dE}{dx} = \text{constant}$$

$$B' \equiv \frac{dB}{dx} = \text{constant}$$




Magnetic quad

Note: Bigger beams require bigger fields.

# Focusing in the Accelerator

Modern accelerators use Alternating Gradient (AG) Focusing.

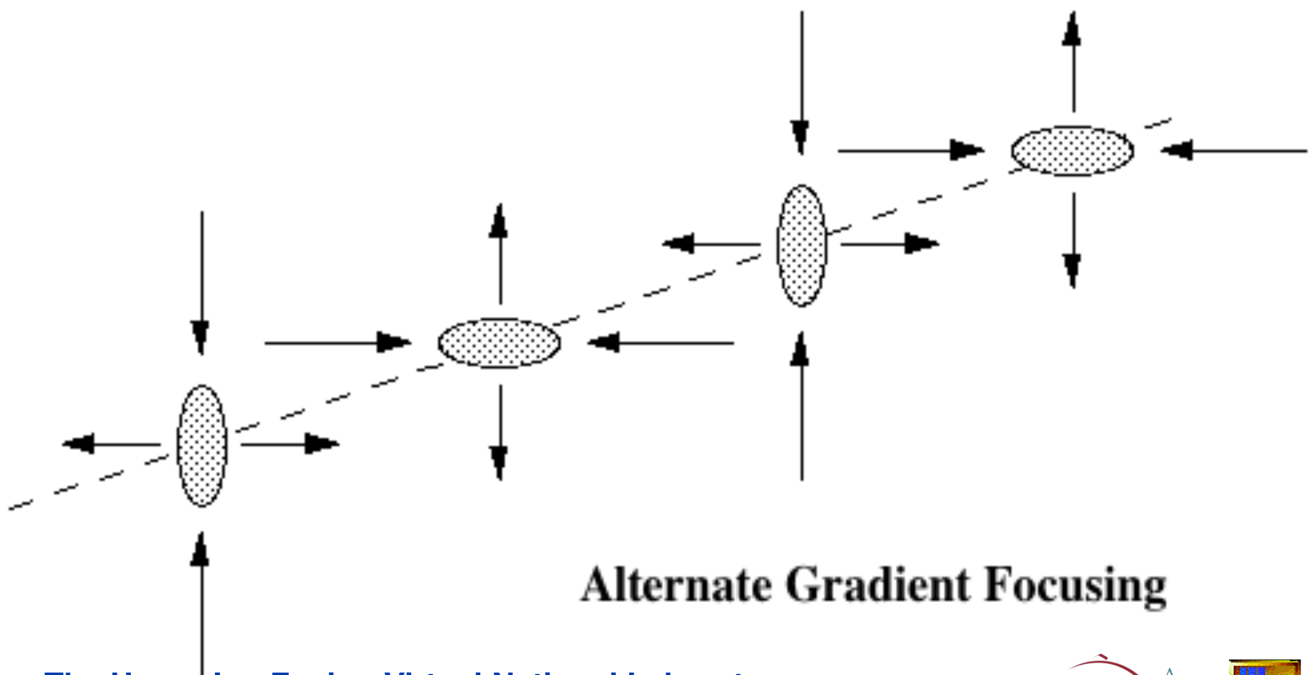
$$F_x = -\,qE'\,x \quad \text{or} \quad -qvB'\,x$$

$$F_y = +\,qE'\,y \quad \text{or} \quad +qvB'\,y$$

Quadrupoles give linear forces.

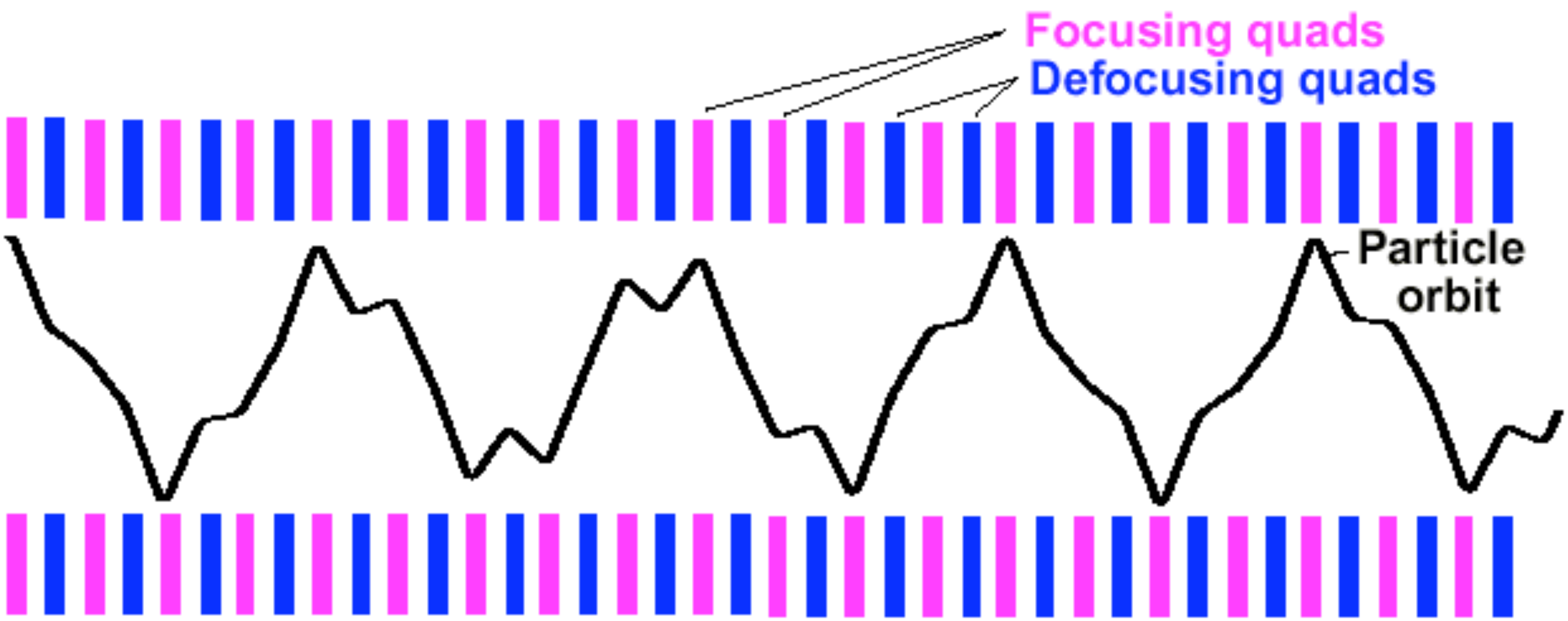
Note: $E' \equiv \frac{dE}{dx}$ $B' \equiv \frac{dB}{dx}$

Also called “strong focusing”



Alternate Gradient Focusing

# Single Particle Orbit - no space charge

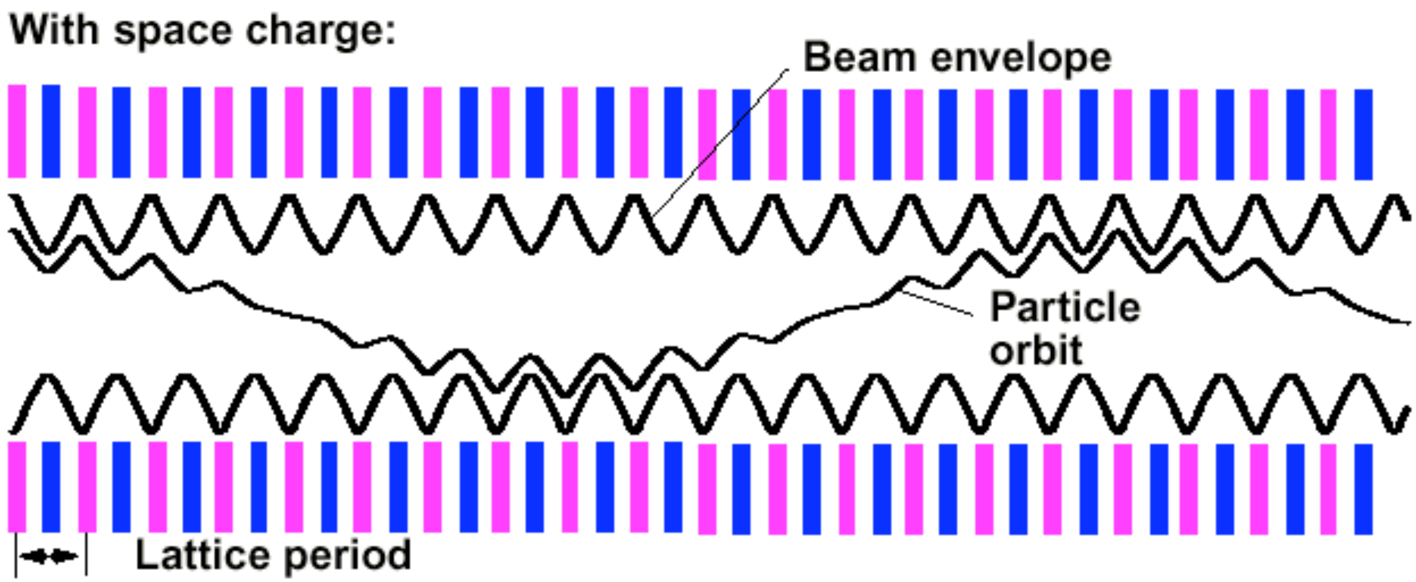


# Transervse beam dynamics. RMS parameters described by the envelope equation.

$$\mathbf{a}'' = -\mathbf{ka} + \frac{\varepsilon^2}{\mathbf{a}^3} + \frac{2\mathbf{K}}{\mathbf{a}+\mathbf{b}} \qquad \mathbf{K} \equiv \frac{\mathbf{q}\lambda}{2\pi\,\varepsilon_0 \mathbf{mc}^2\beta^2\gamma^3} \qquad \mathbf{k} = \frac{\mathbf{qE}'}{\mathbf{mv}^2} \quad \text{or} \quad \frac{\mathbf{qB}'}{\mathbf{mv}}$$

For HIF,

$$\frac{2\mathbf{K}}{\mathbf{a}+\mathbf{b}} >> \frac{\varepsilon^2}{\mathbf{a}^3}$$



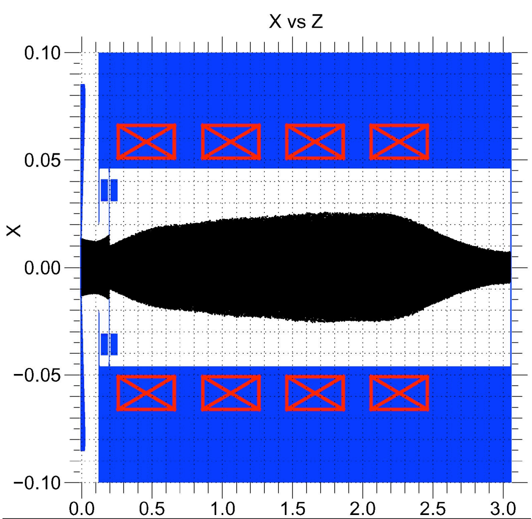

Except at the target, beam is space-charge dominated.

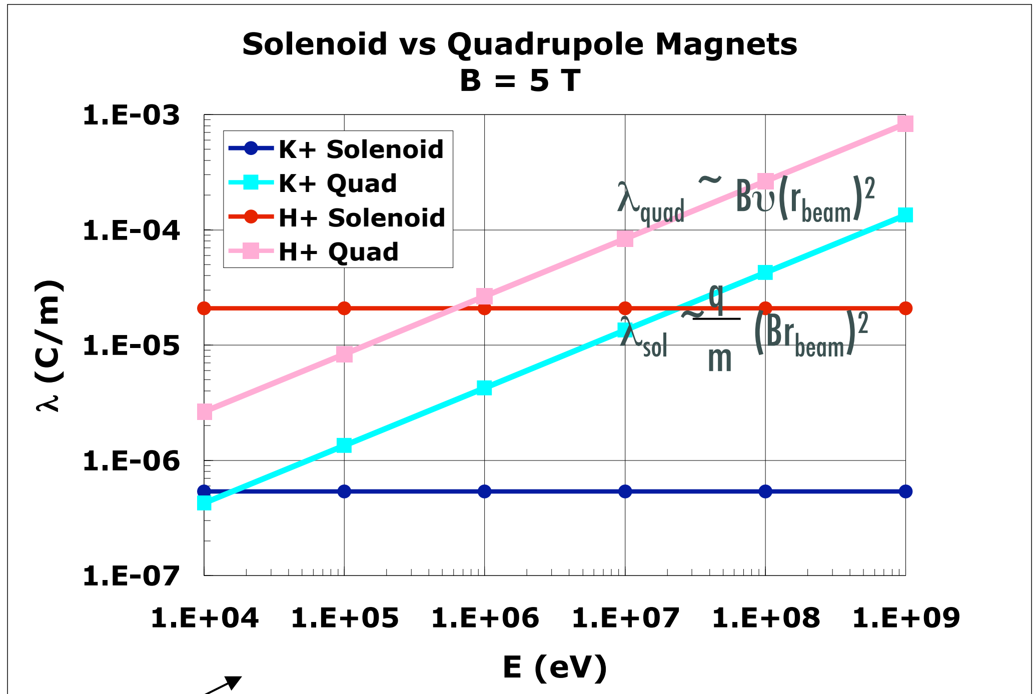
Depressed phase advance $\sigma << \sigma_o$. For quiescent transport, $\sigma_o < 90^o$

# Beam envelope for solenoid focusing

$$a'' = -ka + \frac{\varepsilon^2}{a^3} + \frac{2K}{a+b} \qquad K \equiv \frac{q\lambda}{2\pi\varepsilon_0 mc^2\beta^2\gamma^3} \qquad k = \frac{qE'}{mv^2} \quad \text{or} \quad \frac{qB'}{mv}$$

$$\boxed{k_{sol} = \left(\frac{qB_z}{mv}\right)^2}$$




Assume: $r_{beam}$ = 25 mm or .7 $r_{pipe}$

$K > \varepsilon^2/r^2$ $\qquad$ $K \sim 10^{-3}$

# More mathematical picture of the beam edge ... the "Envelope Equation"

focusing force of quadrupoles

space charge force*

$$x'' = -kx + \frac{2K}{a(a+b)}x$$

$$\overline{xx''} = -k\overline{x^2} + \frac{2K}{a(a+b)}\overline{x^2}$$

Use $\overline{x^2}'' = 2(\overline{xx''} + \overline{x'^2})$

$$\varepsilon^2 = 16\pi\left(\overline{x^2}\,\overline{x'^2} - \overline{xx'}^2\right)$$

* elliptical uniform beam used as example

Where:

$K \equiv \dfrac{q\lambda}{2\pi\varepsilon_0 mc^2\beta^2\gamma^3}$ = dimensionless perveance

$k = \dfrac{qE'}{mv^2}$ or $\dfrac{qB'}{mv}$

$\bar{f} \equiv$ avg of $f$ over distribution function

$\varepsilon \equiv$ emittance in x direction

Then if $a = 2\sqrt{\overline{x^2}}$,

$$\boxed{a'' = -ka + \frac{\varepsilon^2}{a^3} + \frac{2K}{a+b}}$$

Envelope Equation

Focusing Fields oppose Emittance and Space charge.

For HIF, $\dfrac{2K}{a+b} >> \dfrac{\varepsilon^2}{a^3}$ Except at the target, beam is space-charge dominated.

# Beam Physics issues

In accelerator

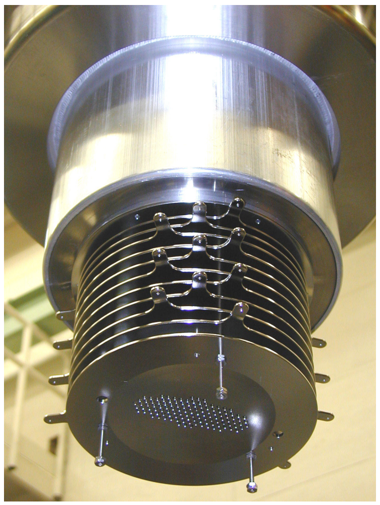
- quality of injected beam
- emittance degradation
- “halo” generation
- instabilities
- stray electrons
- longitudinal drift compression
- multiple beam effects
- focusing aberrations

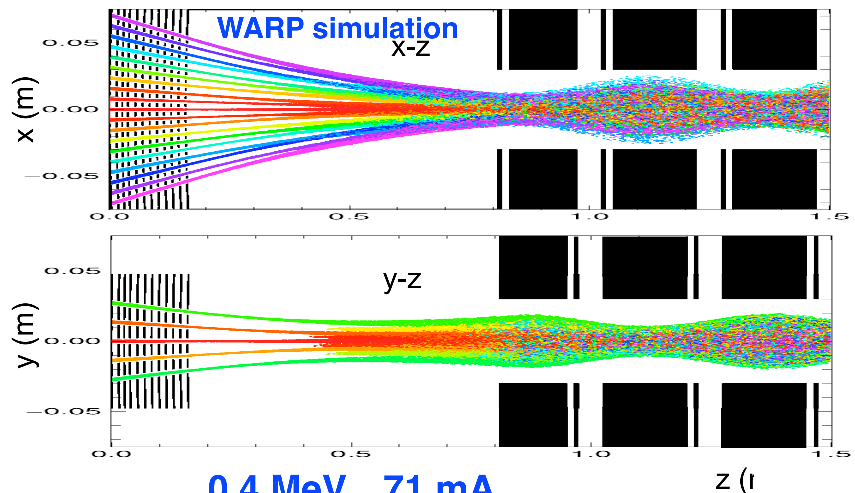
In fusion chamber

- ionization of beam and background
- imperfect neutralization
- Instabilities
- self-magnetic and inductive effects
- multiple beam effects

# High current, low emittance ion sources

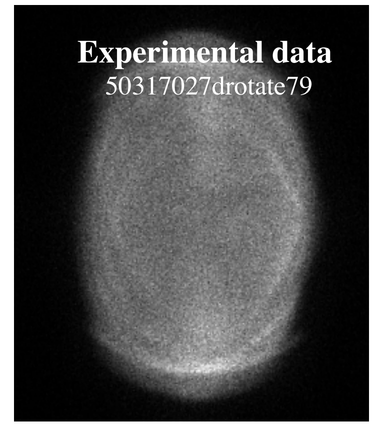
## **Surface ionization sources** and **multi-aperture gas sources**

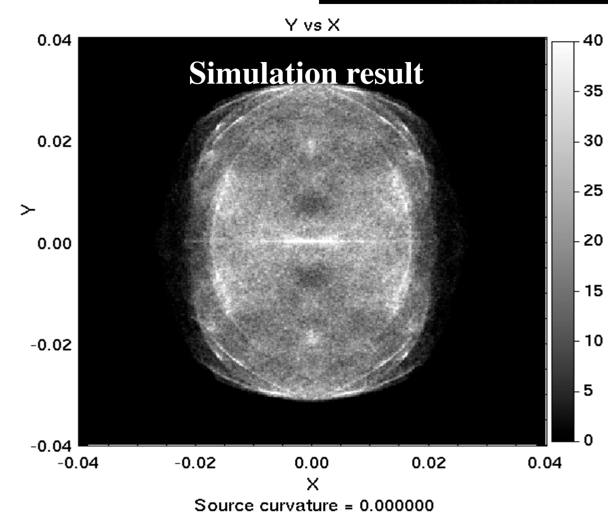





**0.4 MeV 71 mA**

**1.6 MeV 568 mA**



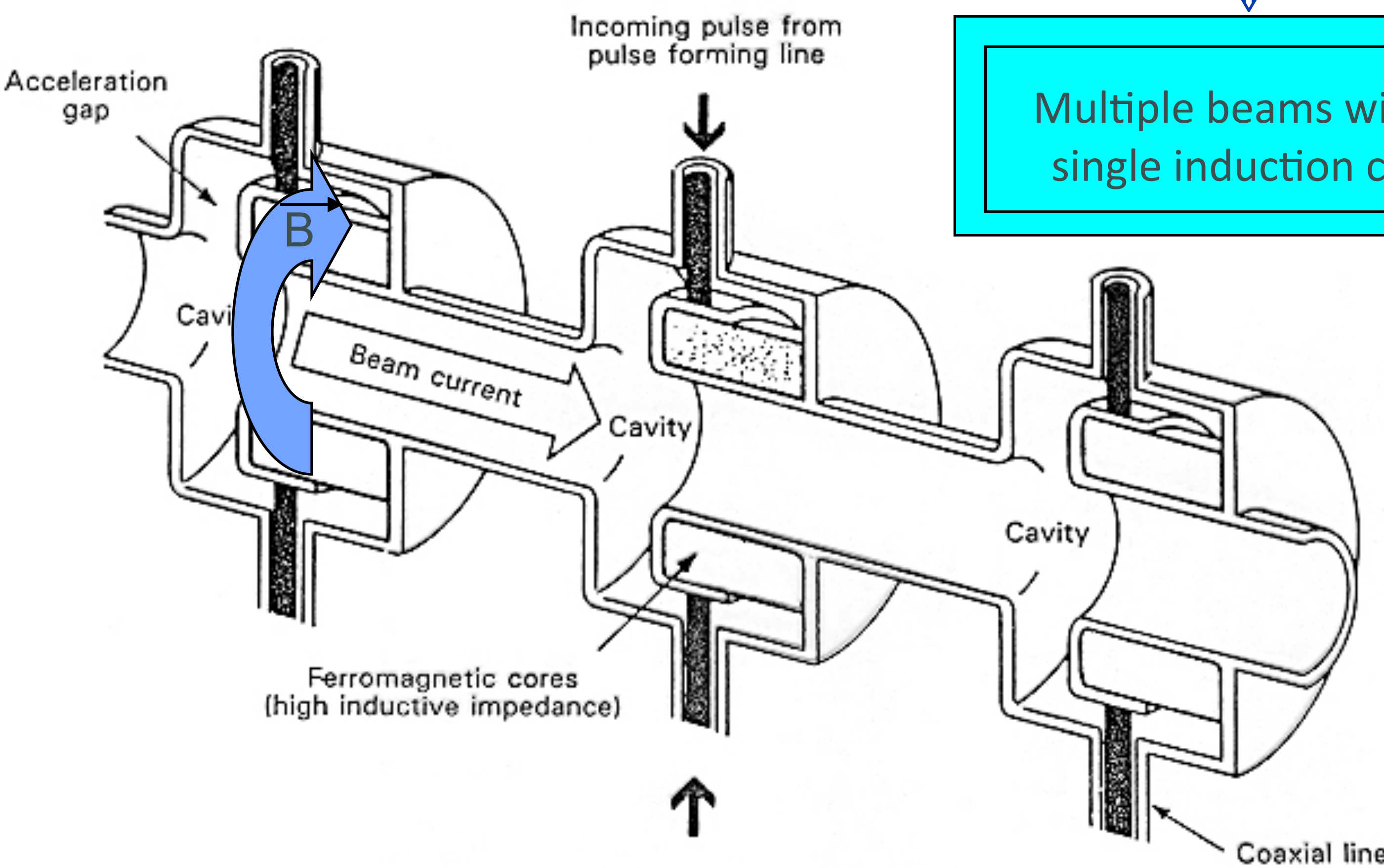



# Induction acceleration efficiently accelerates high current beams

Efficiency increases as beam current increases

⇓

Multiple beams within single induction core




$$V = \frac{\Delta B \cdot \text{area}}{\tau}$$

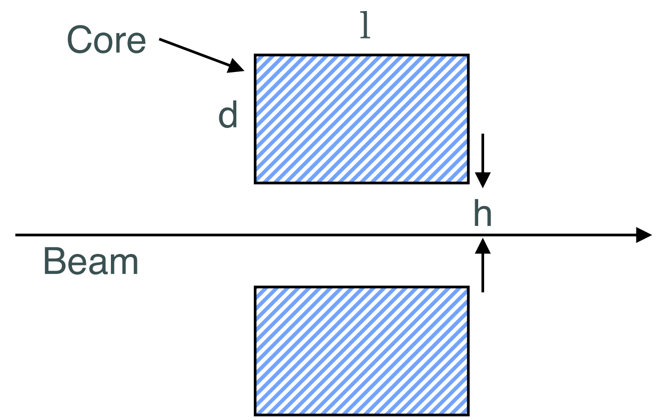
Schematic cutaway of an induction Linac

# Why We Chose Induction

It handles high currents naturally.

$$\text{Efficiency} = \frac{Ild\frac{\Delta B}{\tau}\tau}{\underbrace{Ild\frac{\Delta B}{\tau}}_{\text{Voltage across gap}}\tau + w\,\underbrace{\pi ld(2h+d)}_{\text{Core volume}}}$$

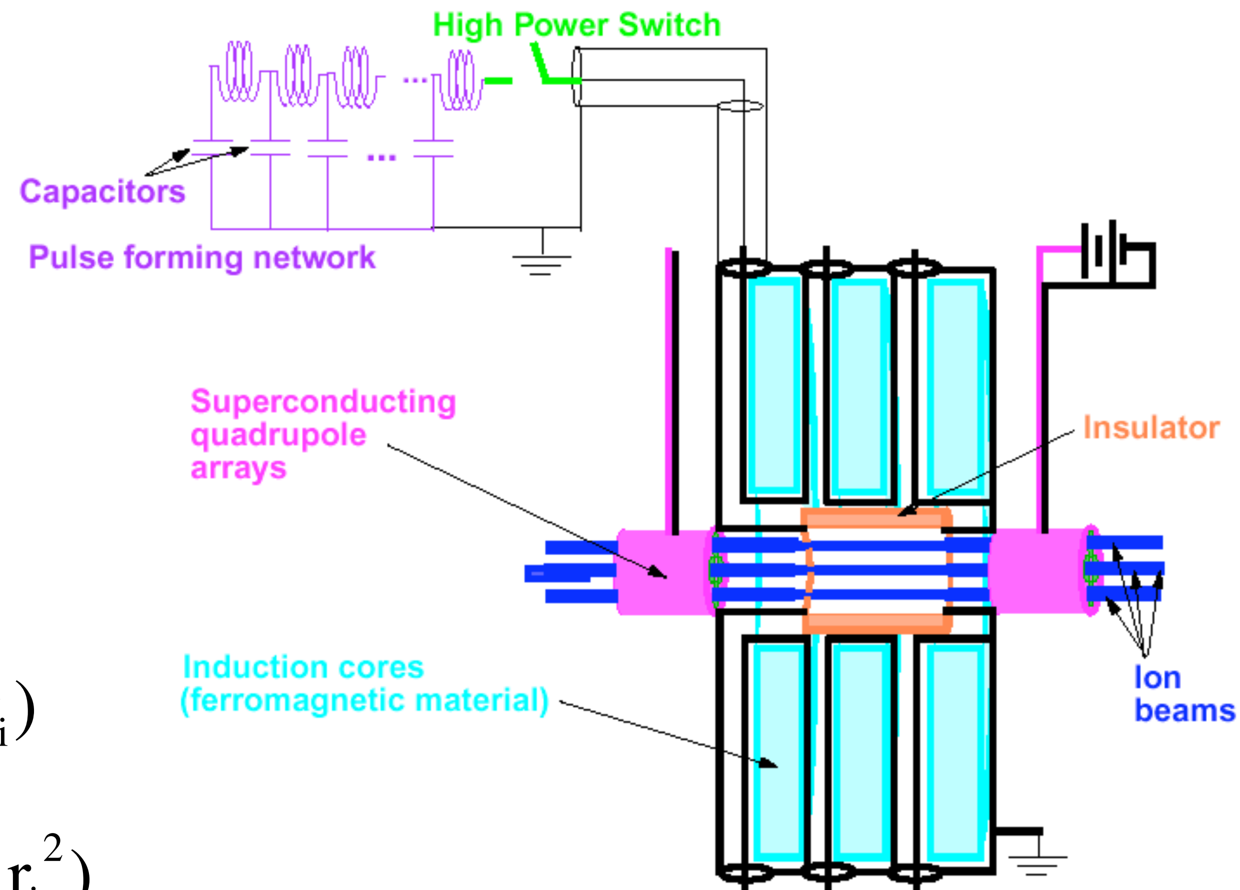
Loss function (frequency dependent)




$$= \frac{I\Delta B}{I\Delta B + w\pi(2h+d)}$$

Efficiency increases as current increases $\Rightarrow$ Multiple beams within single induction core

# The Focusing Lattice of Quads Alternates with Induction Cores




$$\text{area} \propto (r_o - r_i)$$

$$\text{mass} \propto (r_o^{\,2} - r_i^{\,2})$$

Premium on compact transverse focusing structures

# Induction is used to accelerate high peak currents (up to 1 kA) by inducing longitudinal electric fields in a sequence of gaps

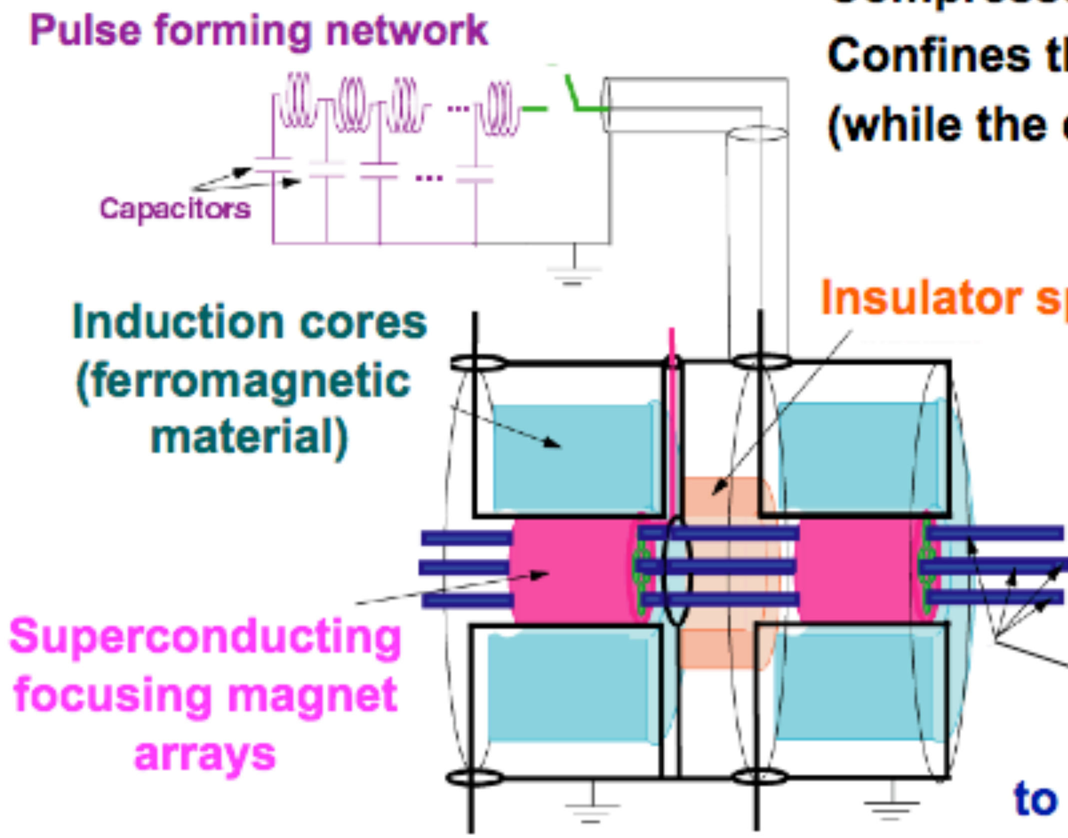
The electric field in the gap does three things:

Accelerates the beam

Compresses the beam

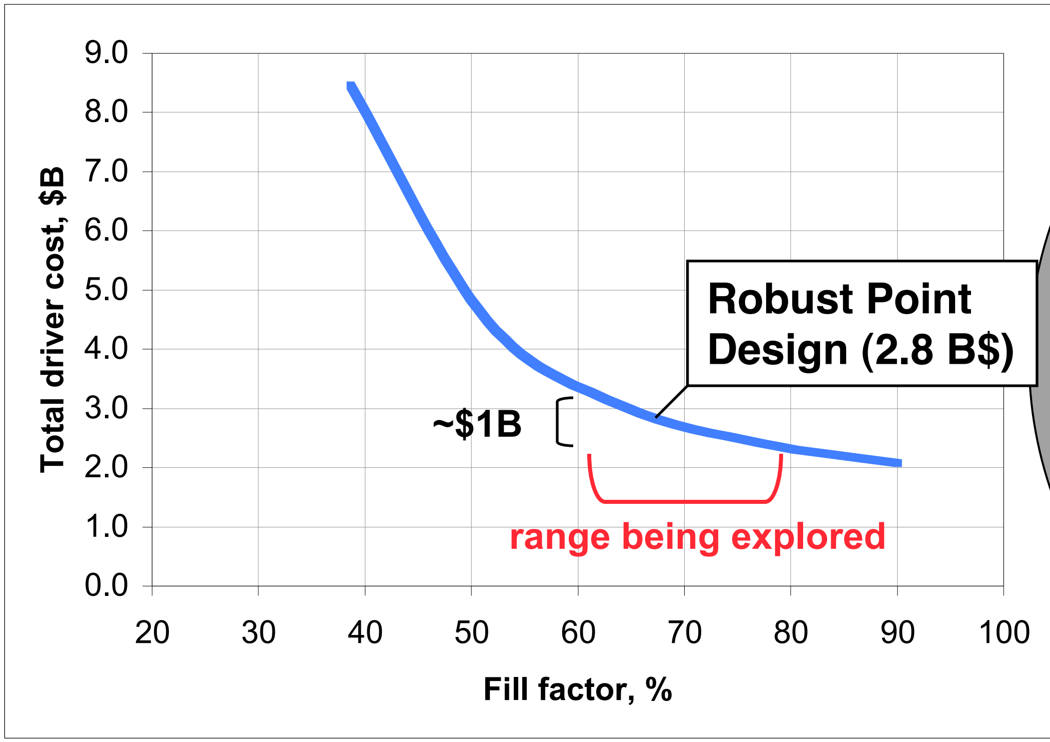
Confines the beam longitudinally

(while the quadrupoles confine beam transversely)

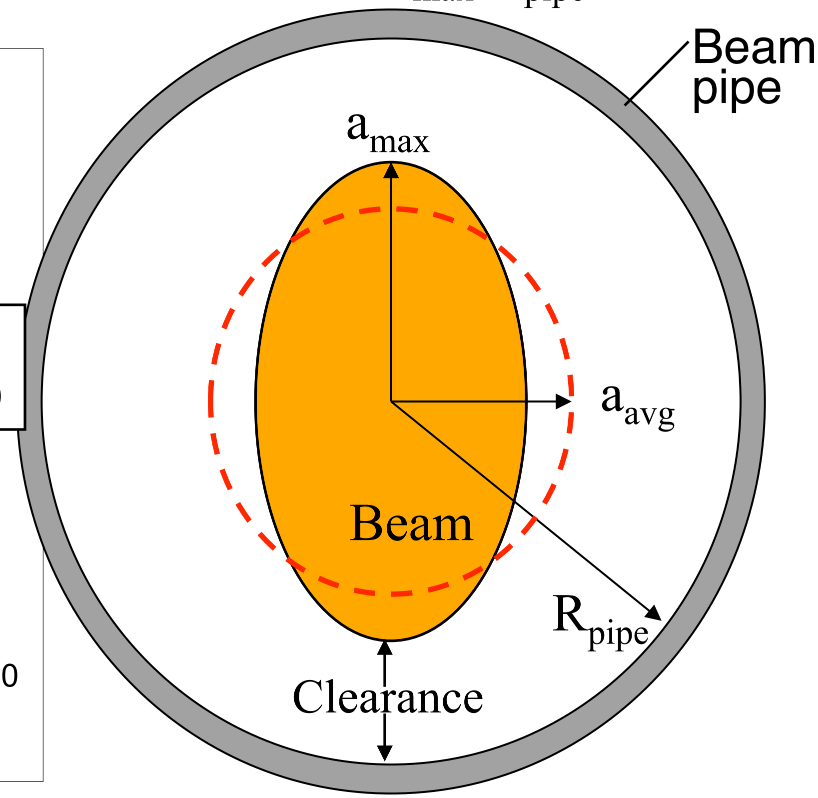


# System studies show that driver cost is very sensitive to fill factor

**IBEAM results:**

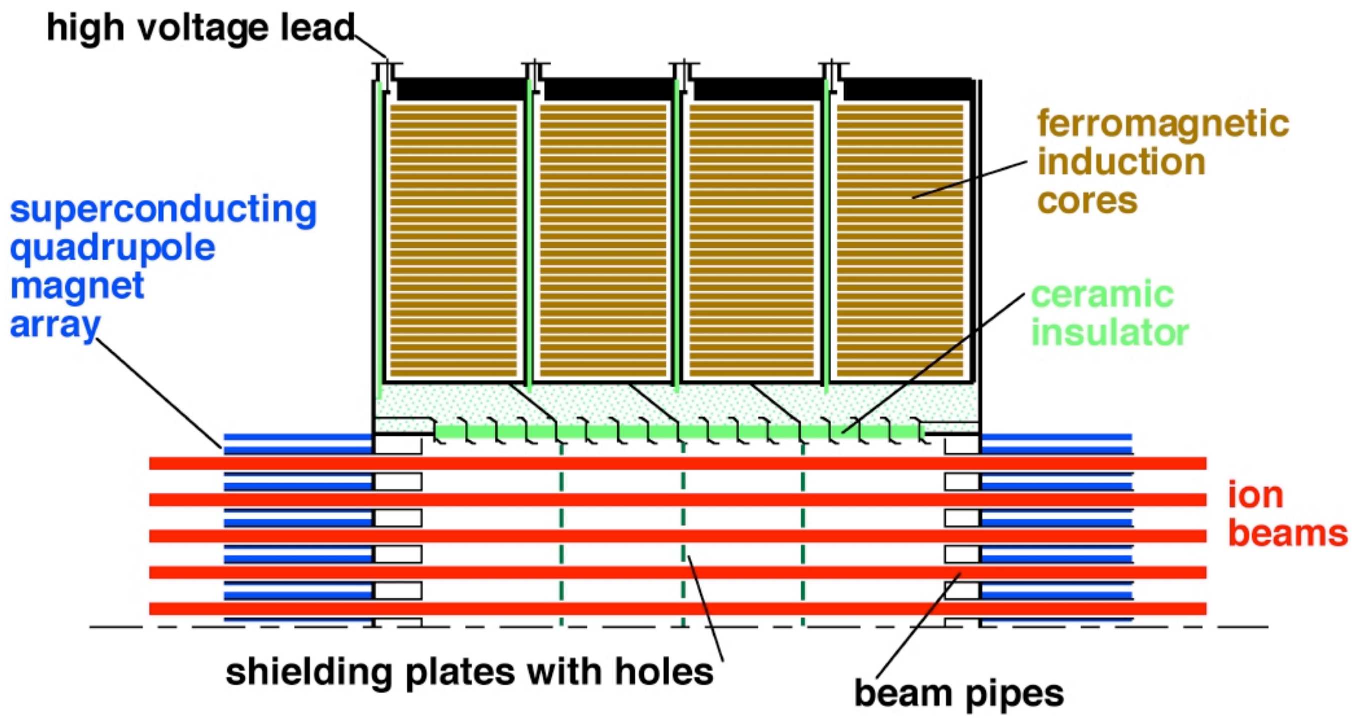



Fill factor = $a_{max}/R_{pipe}$




**(fixed number of beams, initial pulse length, and quadrupole field strength)**

# Multiple beams within single induction core




(some designs: multiple accelerators with single beams)

# An Induction Core

# Superconducting array coils share flux with neighboring cells. Enhances field ≈30%

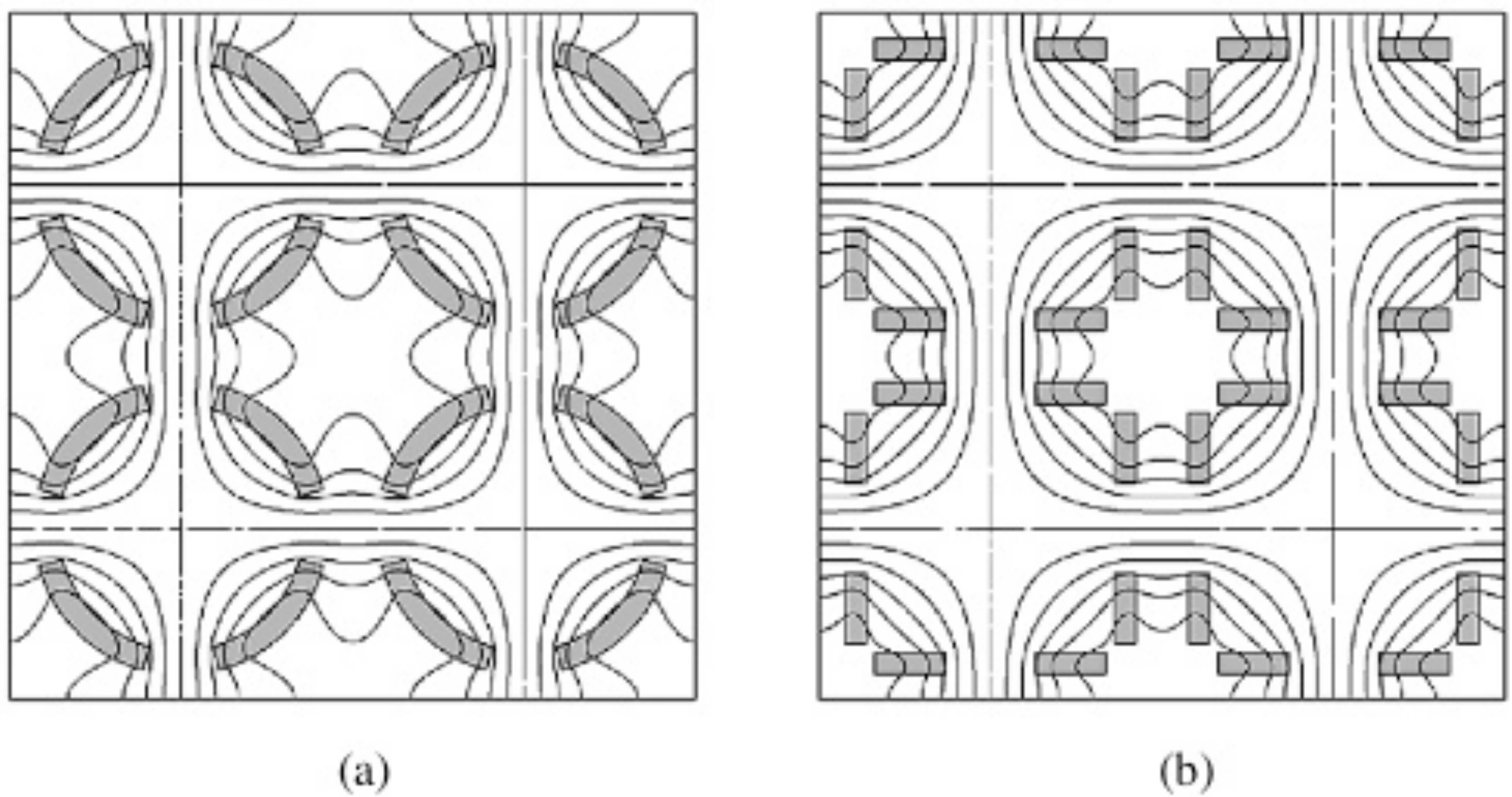



Fig. 2. Array configurations using (a) shell or (b) block coils.

# Example: 4-beam electrostatic quadrupole array

$V = \pm\ 60$ kV,

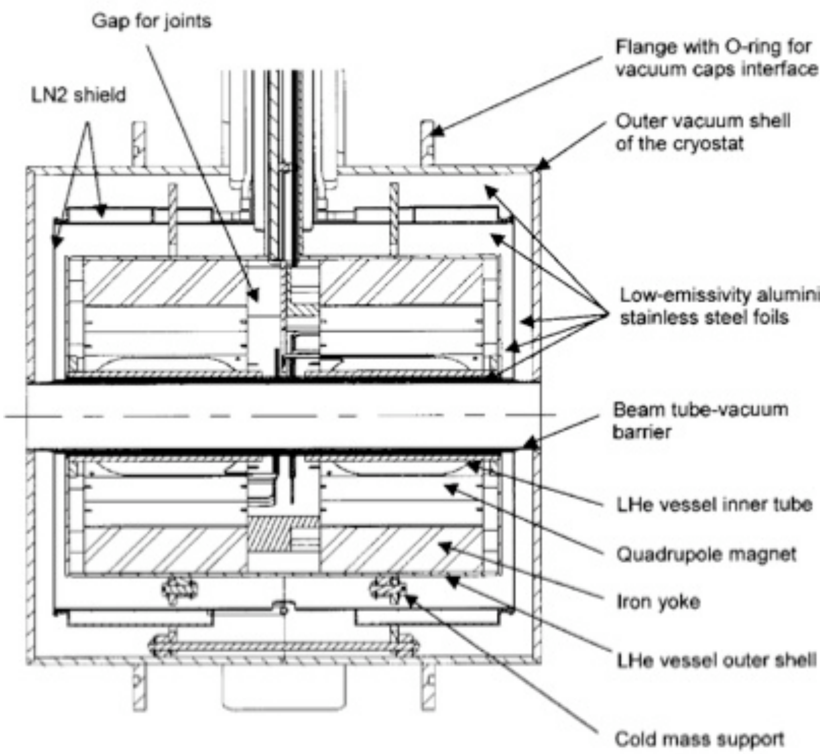
46 mm bore,

$\lambda \approx 0.25\ \mu C/m/channel$

naturally clears e-clouds

# Superconducting magnet development

Prototypes reached 100% $I_{ss}$ after a few quenches.
Flat coils, warm bore (59 mm $\phi$)

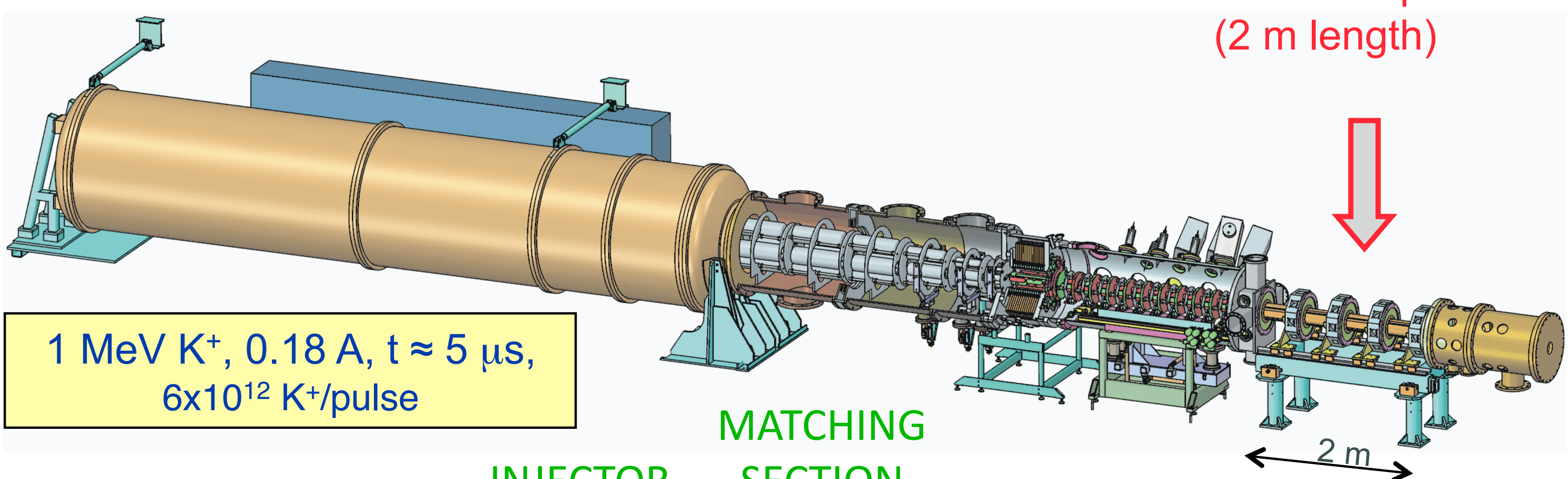



Quadrupole doublet
in Cryostat

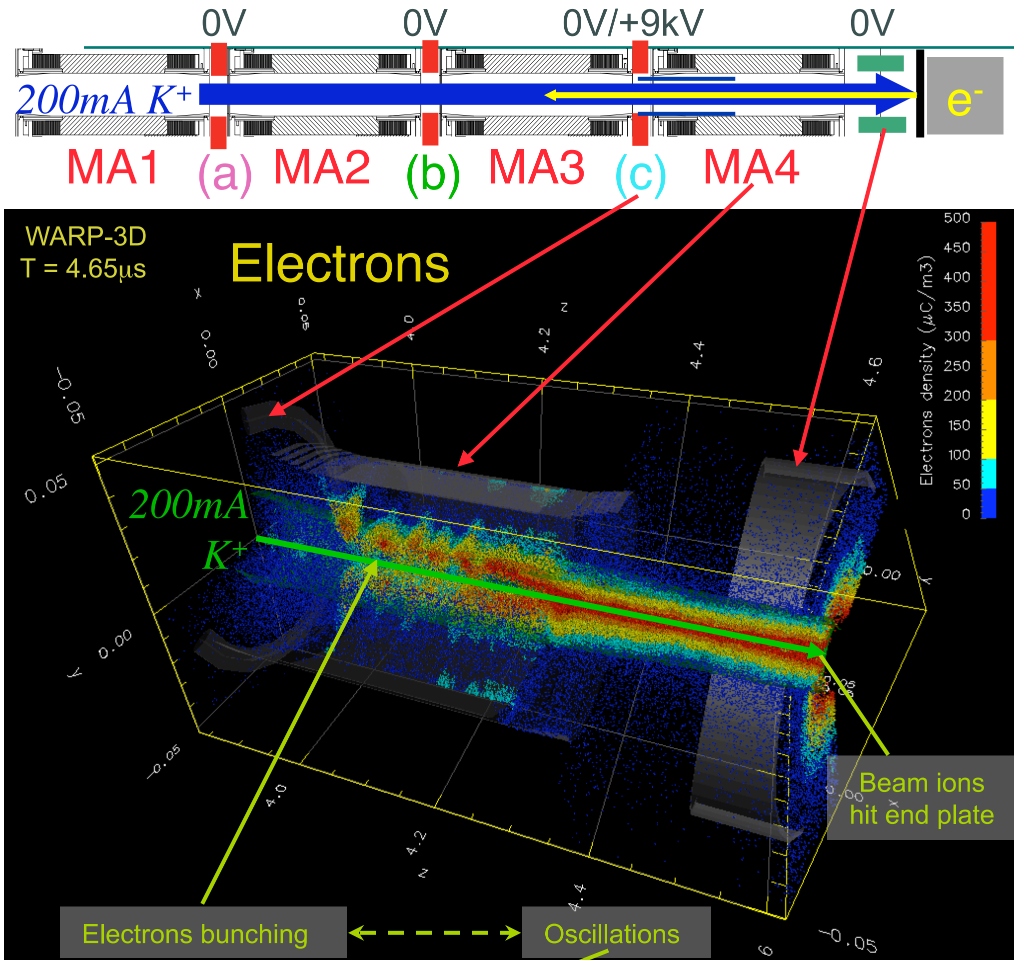
$G(I_{ss})$ = 132 T/m. $I_{op}$ = $0.85I_{ss}$
$L_{eff}$ = 104.5 mm. suitable for 2 MeV beam.
Field quality: <0.5% at R= 25 mm (integrated)

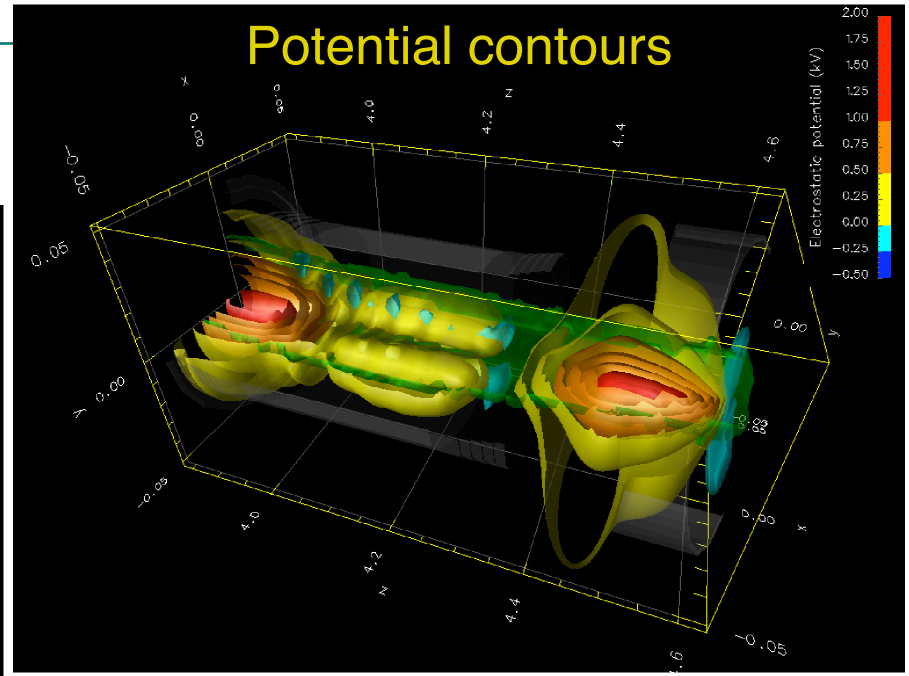
# Injection, matching, low-energy transport at driver scale

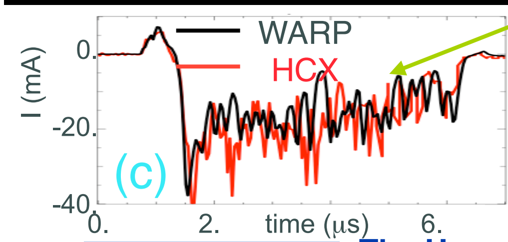
low energy heavy ions



# Simulation discovered oscillation (λ~5 cm) growing from near center of 4th quadrupole. Seen also in experiment.

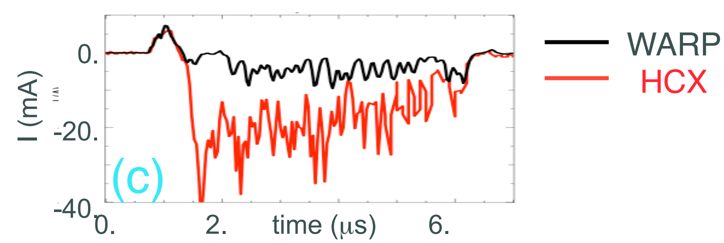


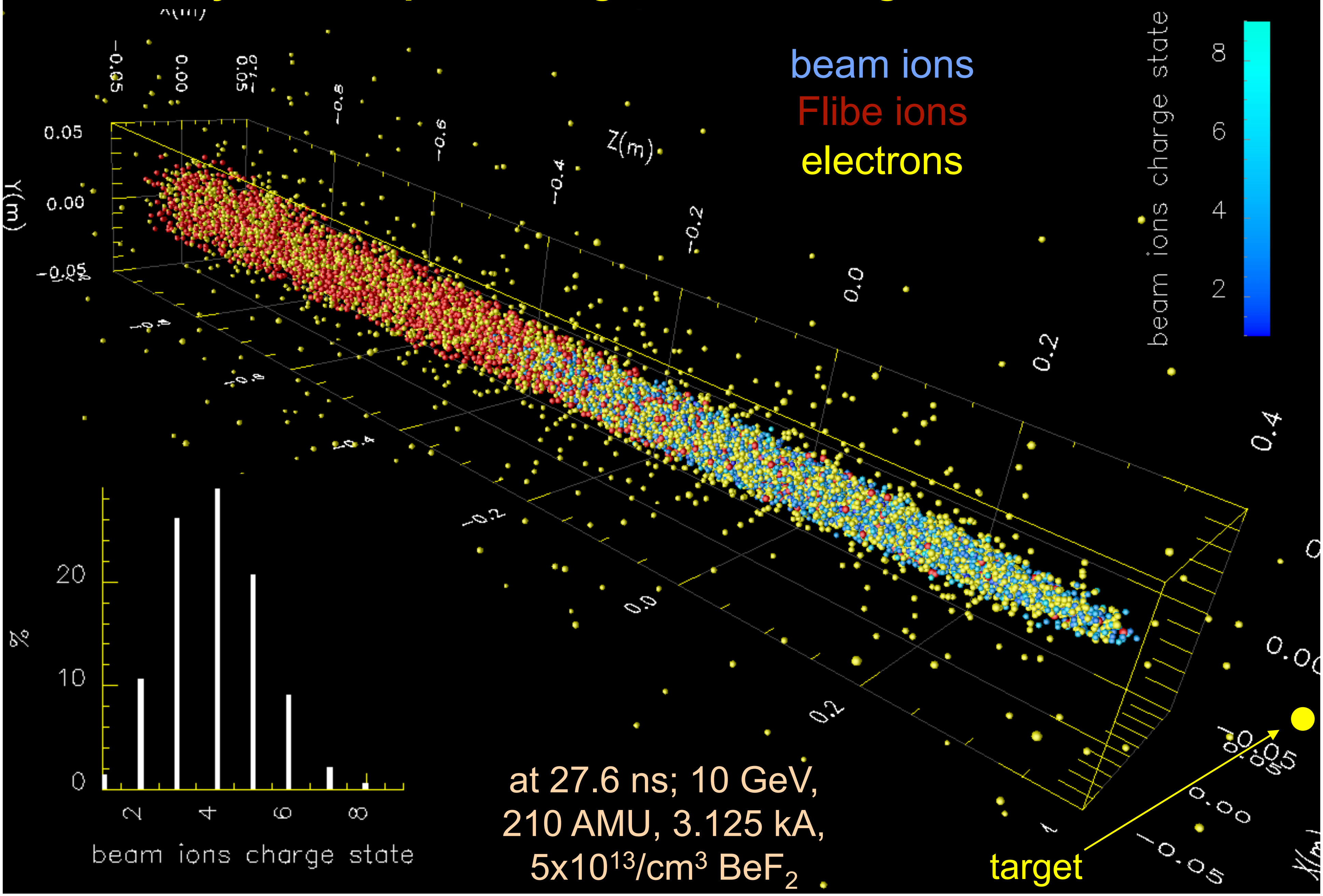




~6 MHz signal in (C) in simulation AND experiment

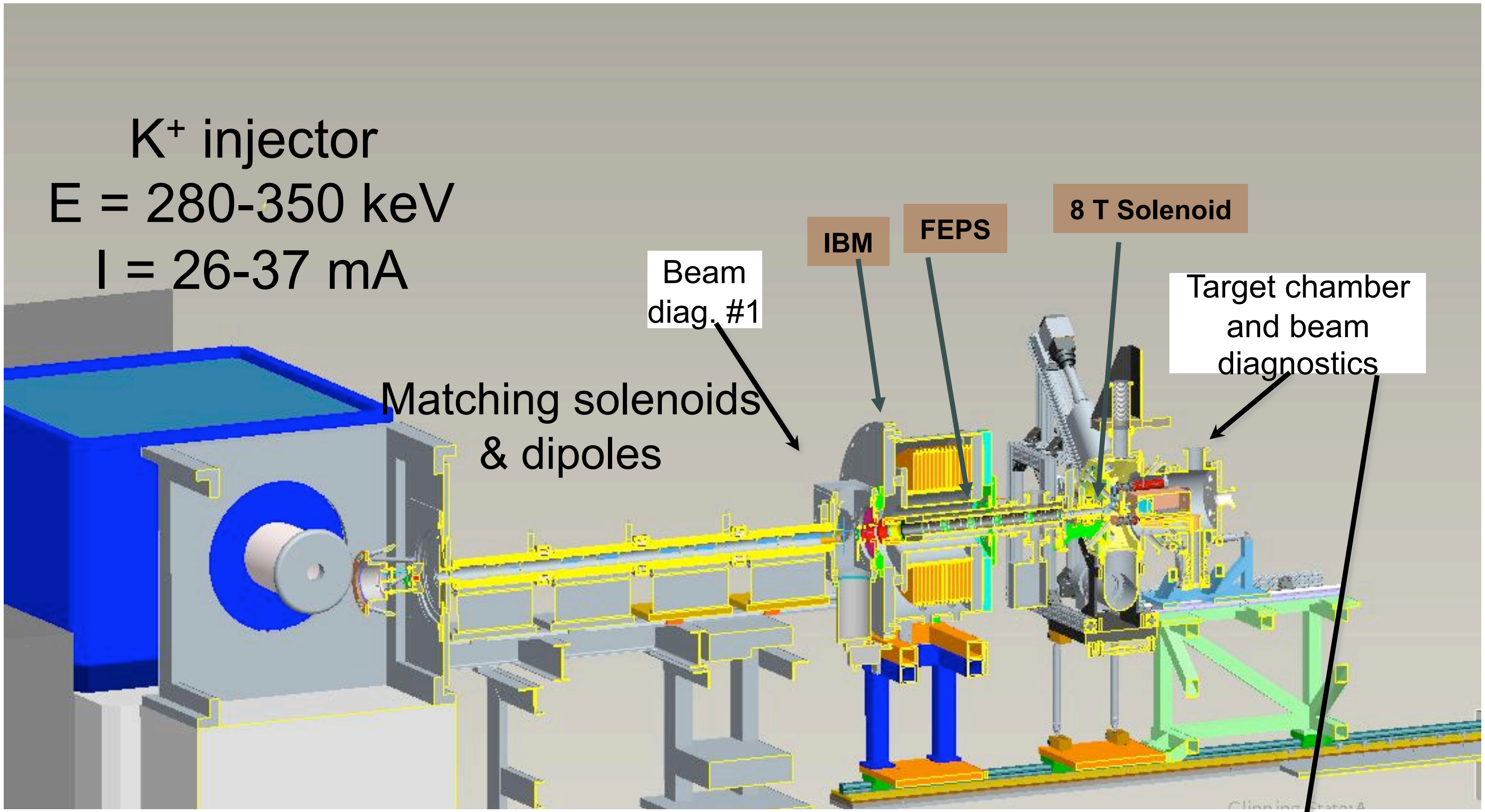
1. Good test of secondary module - no secondary electrons:



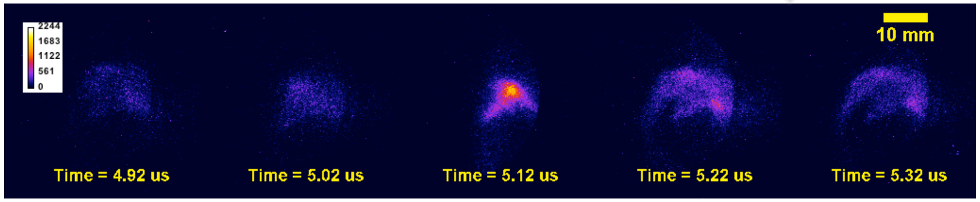
## 3-D computer simulation suggest that neutralizing the beam would effectively cancel space charge and allow a good focus



# NDCX-1 has demonstrated simultaneous transverse focusing and longitudinal compression




**Objectives:** **Preservation of low emittance, plasma column with $n_p > n_b$, ($\varepsilon_{ni}$ = 0.07 mm-mrad, $n_{b\text{-init}} \approx 10^9$ /cm$^3$, $n_{bmax} \approx 10^{12}$ /cm$^3$ now, later, $\approx 10^{13}$ /cm$^3$)**



# Cross cutting accelerator and beam physics research topics

- High current, high brightness ion injectors: These must deliver ~1 Ampere level current (if singly ionized), with low emittance. The bunch duration is a few to 20 msec at 5-10 Hz. Breakthroughs here will benefit research areas requiring high intensity hadron beams. Reliability and lifetime must be improved.
- Reliable, high field transverse focusing: solenoids, magnetic quadrupoles, electrostatic quadrupoles.
- Multi-beam induction accelerator module design and single beam induction accelerator design.
- Electron clouds and beam background gas interactions. This is cross-cutting with e-cloud research in HEP and high intensity accelerators.
- Beam loss, halo characterization and mitigation
- Axial beam compression and methods to compensate or correct for chromatic aberrations.
- Beam - plasma instabilities.

# Technology development must accompany beam experiments

The main cost centers of an induction linac for inertial fusion:

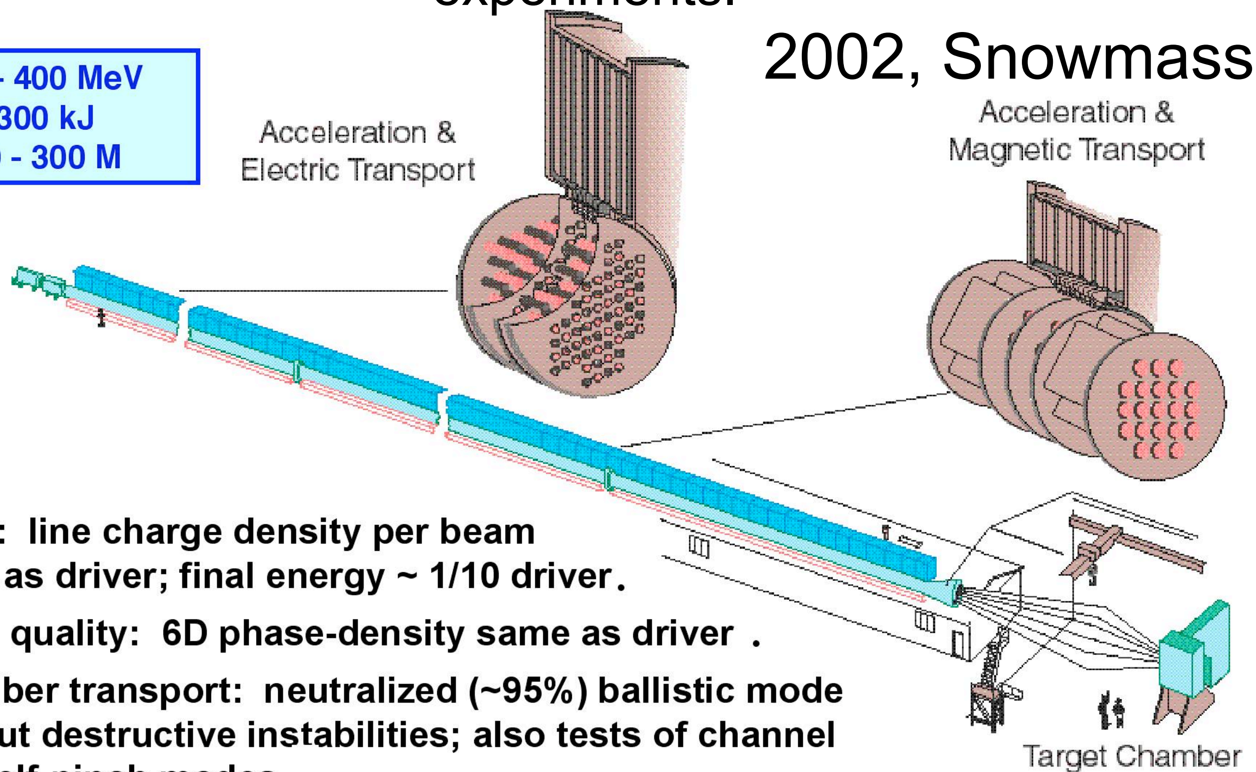
- multi-beam quadrupole arrays
    - Nb3Sn, edge termination,…
- insulators
    - Glassy ceramics, embedded rings for grading
- ferromagnetic materials for the induction cores
    - Interlaminar insulation, annealing
- pulsers.

# Toward heavy ion fusion, an experimental target testing and accelerator facility

The Integrated Research Experiment (IRE) concept (2002): integrate beam dynamics, driver technology with HIF specific indirect drive target physics experiments.

2002, Snowmass

~ 200 - 400 MeV
~ 30 - 300 kJ
~ $150 - 300 M




**Scale: line charge density per beam same as driver; final energy ~ 1/10 driver.**

**Beam quality: 6D phase-density same as driver .**

**Chamber transport: neutralized (~95%) ballistic mode without destructive instabilities; also tests of channel and self-pinch modes .**

**Chamber technology: test driver/chamber interface .**

**Target temperature: 50 - 100 eV.**

## The near-term objective this program would be the design of two facilities:

- A prototype experimental facility, capable of doing hybrid-relevant fusion target experiments at >100 eV, integrated with all key ion beam manipulations.

- A demonstration power plant design.


**REFERENCES**

[1] 1979 Foster Committee; 1983 Jason Report (JSR82-302); 1986 National Academies of Sciences Report; 1990 Fusion Policy Advisory Committee report (Stever Panel); 1993 Fusion Energy Advisory Committee (Davidson Panel); 1996 FESAC report (Sheffield Panel)

[2] W.R. Meier, Overview of chamber and target technology R&D for heavy ion fusion, Nucl. Inst. Meth. A, **464**, (2001) 103.

W.R. Meier et al, IFE CHAMBER TECHNOLOGY – STATUS AND FUTURE CHALLENGES, Fusion Science and Technology, **44,** (2003) 27. http://www-ferp.ucsd.edu/NAJMABADI/PAPER/A1-072-03-FST-Meier.pdf

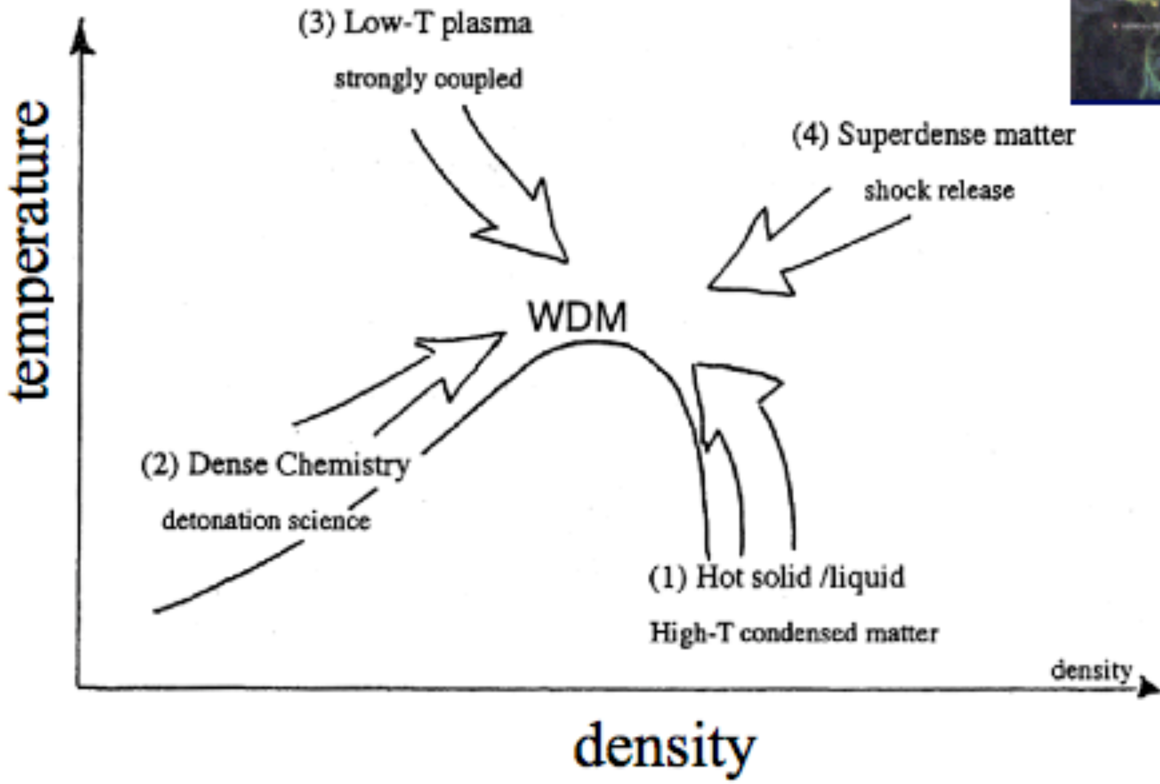
[3] S. Yu et al., Fusion Sci. Tech. **44**, 2 (2003) 329.

[4] D.A. Callahan-Miller and M. Tabak, Phys. Plasmas **7**, 5 (2000) 2083.

[5] B.G. Logan, L. J. Perkins, and J. J. Barnard, Phys. Plasmas **15** (2008) 072701.

**The WDM regime is at the meeting point of several distinct physical regimes - a scientifically rich area of High Energy Density Physics.**

From R. More, Warm Dense Matter School, LBNL, Jan. 10-16, 2008.
http://hifweb.lbl.gov/wdmschool/


Interesting phenomena at: $0.01\ \rho_{solid} < \rho < 1.0\ \rho_{solid}$
and $0.1\ \text{eV} < T < 10\ \text{eV}$

Unknown properties:
EOS ($p(\rho,T)$, $E(\rho,T)$)
Liquid-vapor boundary
Latent heat of evaporation
Evaporation rate
Surface tension
Work function
Electrical conductivity
dE/dX for hot targets

Phenomena:
Metal-insulator transition
Phase transitions?
Plasma composition?

# NDCX-2: 3-6 MeV, for T ≈ 1 eV target heating and WDM studies